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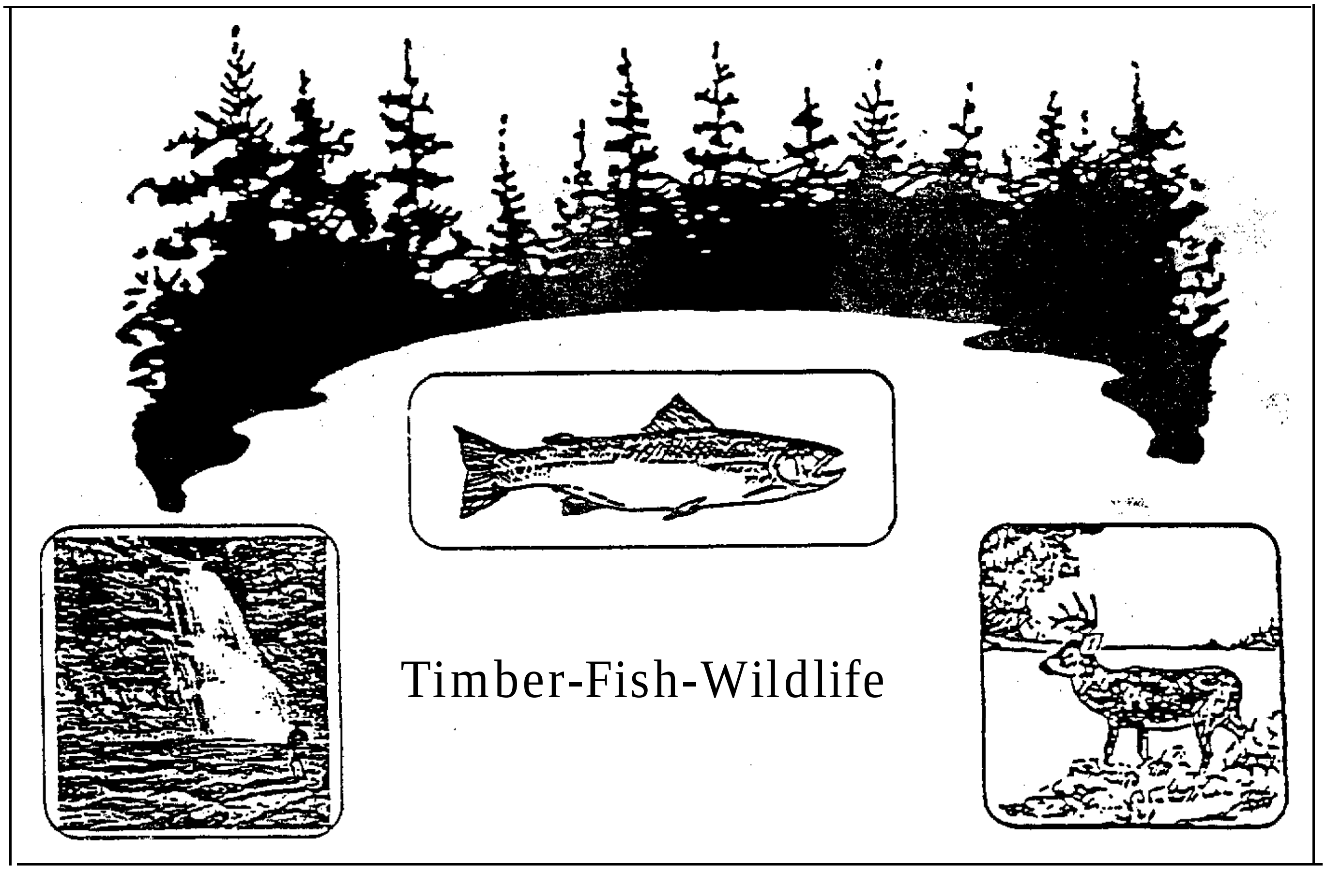
TFW-WQ5-91-004

TIMBER-FISH-WILDIFE

EVALUATION OF DOWNSTREAM TEMPERATURE EFFECTS OF TYPE 4/5 WATERS



JUNE 1991

Evaluation of Downstream Temperature Effects of Type 4/5 Waters

T/F/W Report No. WQ5-91-004

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Disclaimer

The opinions, findings, conclusions or recommendations expressed in this report are those of the authors and do not necessarily reflect the views of any participant in, or committee of, the Timber/Fish/Wildlife Agreement, the Washington Forest Practices Board, or the Department of Natural Resources, nor does mention of trade names or commercial products constitute endorsement or recommendation of use.

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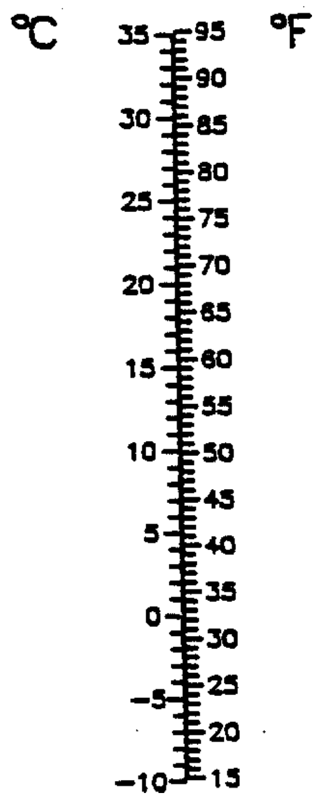
CONVERSION TABLES

Multiply Metric Units	BY	To Obtain English Units
Meters (m)	3.28	Feet (ft)
Kilometers (km)	0.621	Miles (mi)
Sq. Kilometers (km^2)	0.386	Sq. Miles (mi^2)
CMS (m^3/s) (cubic meters per second)	35.314	CFS (ft^3/sec) (cubic feet per second)

Degrees Celsius to Degrees Fahrenheit: $^{\circ}C = (^{\circ}F - 32)(0.55)$

Degrees Fahrenheit to Degrees Celsius: $^{\circ}F = (1.8)(^{\circ}C) + 32$



I. Executive Summary

Streams in Washington State are classified, with respect to forest practices, into one of five water types (WAC 222-16-030). Stream Types l-3 include, by definition, all larger streams and shorelines of the state. Any stream with a late-summer base flow greater than 0.009 cms (0.3 cfs), and any stream that supports a significant fish population, is classed Type 1, 2 or 3. Stream Types 4 and 5 are generally small headwater streams that do not support significant fish populations. Current forest practices regulations do not require any riparian trees to be left after harvest on Type 4 and 5 streams, as they do on stream Types 1-3.

The possibility of temperature impacts from removal of riparian trees along Type 4 waters on downstream, salmonid-bearing waters has remained a concern within T/F/W. This study investigates the effect on stream temperatures of forest practices along Type 4/5 waters in Washington. Consideration is given to both stream temperature effects within the Type 4/5 water as well as potential downstream temperature effects in fish bearing waters.

This study supplements a previous study (Sullivan and others, 1990) which investigated stream temperatures for larger Type l-3 rivers and streams in Washington. It was anticipated that stream temperatures in Type 4/5 streams would behave similarly with respect to two basic principles reported for larger streams. First, stream temperature tends towards equilibrium with the surrounding environmental conditions. The interaction between temperature and environmental conditions occurs in a complicated yet predictable manner. Second, the maximum equilibrium temperature for a stream reach (the hottest temperature reported for a stream reach) can readily be categorized with minimal information; specifically shade and elevation. However, we would also anticipate temperatures in smaller streams to be much more responsive to localized factors such as groundwater.

Three primary objectives of this study were:

1) Characterize temperature regimes in Type 4 waters of Washington.

2) Assess the magnitude and extent of downstream effects related to water temperatures of upstream Type 4 waters.

3) Provide recommendation for management of riparian areas on Type 4 waters relevant to potential downstream temperature impacts.

All study objectives were met, except that the streams surveyed were limited to western Washington. In summer 1990 air and water temperatures were monitored at multiple points along the 4/3 water type interface for nine locations in western Washington. The conclusions and recommendations within this report are based upon the results of this monitoring.

Maximum water temperatures within Type 4 streams where the riparian overstory had been removed ranged between 13.5 and 23.1°C. Although the sample size was small, environmental conditions appear to effect Type 4 stream temperatures in similar predictable ways as reported for larger streams (Sullivan and others, 1990). Water temperatures in the Type 4 streams studied are influenced by air temperatures as evidenced by similar diurnal patters. However, there is a maximum equilibrium temperature above which water temperatures will not increase, even though air temperatures do. Other important characteristics influencing water temperatures in Type 4 streams include shading levels, groundwater temperatures and groundwater proportion of flow, although effects from groundwater seem to be quite localized and to vary between sites. Maximum stream temperatures are strongly influenced by elevation, with warmer temperatures observed at lower elevations.

Higher than expected shade levels were encountered for many Type 4 streams surveyed as part of this study. Where harvest of the Type 4 riparian zone had occurred, logging debris and understory brush still provided substantial shade. Although not verified except by extensive visual observations, it appears that under TFW management, total riparian harvest along Type 4 streams in western Washington is primarily limited to streams substantially smaller than the 0.009 cms (0.3 cfs) upper size limit stated in the regulations for Type 4 waters. Larger streams have been commonly reclassified as Type 3 due to the presence of significant fish populations and landowners are voluntarily leaving buffers on many of the larger Type 4 streams in western Washington.

Type 4 tributaries varying in water temperature and entering as a triiutary to Type 3 streams were found to have very minimal influence on the downstream water temperature. This is primarily because of the size difference in water types. Using a stream flow mixing equation and the relationship between distance from divide and discharge (Sullivan and others, 1990) it was determined that a Type 4 stream as defined by the forest practices regulations could not affect the temperature in a receiving Type 3 or larger water by more than 0.49°C if the confluence is more than 7 km (4.5 miles) distance from divide for the Type 3 stream.

Small streams are very responsive to localized conditions. For single streams transitioning in water type, the harvested Type 4 stream reach responds quickly to increased shade levels as the stream flow passes downstream into shaded Type 3 reach. Stream temperatures quickly come to equilibrium with downstream conditions with the influence of the upstream Type 4 water temperature extending 150 meters or less beyond the water type interface. This distance equates to travel times of one to two hours for equilibrium to become established.

Concern had also been expressed for the potential temperature impacts of multiple Type 4 harvested streams causing cumulative downstream temperature impacts. Since the longitudinal effect of any one Type 4 stream on downstream temperatures is limited to 150 meters or less, cumulative impacts need only be concerned with a small reach. Farther downstream the water temperature would be responding to ambient conditions rather than any temperature effects of the Type 4 stream. A map-based investigation into whether a potential for multiple Type 4 tributaries to be present within the 150-meter zone of influence showed that the average distance between western Washington Type 4 tributaries is on the order of 200 meters or longer, and thus too far apart to contribute to a cumulative impact. In the headwaters of small streams, no situation was observed where more than two Type 4 tributaries combined to form a Type 3 reach. It can be concluded that the downstream temperature effects of Type 4 streams are extremely limited in extent for western Washington. Though this study did not include any eastern Washington sites, is likely that streams in that region would behave similarly.

Management recommendations should be developed after technical review of this report. Management recommendation should recognize the limited downstream temperature effects of timber harvest along Type 4 waters, and that Type 3 waters farther than 7 km from the watershed divide will show virtually no effect from the temperatures of incoming Type 4 tributaries, because the size of the Type 3 stream is too large relative to the size of the Type 4 stream.

This study is not geographically comprehensive, and the number of streams studied was too small to fully characterize the entire range of temperature regimes in all of Washington's Type 4 waters. If shade recommendations are developed for controlling temperatures within Type 4 reaches themselves, it is recommended that additional sites be investigated, using relatively simple maximum-minimum thermometers, to further characterize maximum equilibrium temperatures in ecoregions not studied as part of this project.

The conclusions and recommendations for the management of riparian areas along Type 4 streams are only based on stream temperature concerns. Numerous other factors also must be considered in the management of forest practices along type 4 streams. Though downstream temperature impacts are negligible, erosion and other factors are still relevant to the management of Type 4 streams.

II. Introduction

T/F/W Synopsis

Streams in Washington State are classified, with respect to forest practices, into one of five water types (WAC 222-16-030). Stream Types 1-3 include, by definition, all larger streams and shorelines of the state. Any stream with a late-summer base flow greater than 0.009 cms (0.3 cfs), and any stream that supports a significant fish population, is classed Type 1, 2 or 3.

Stream Types 4 and 5 are generally small headwater streams that do not support significant fish populations, are not used as water supplies, and are not specifically targeted to protect downstream water quality (Macdonald and Ritland, 1989).

A general comparison of Washington's water types with stream classification systems currently used by the Olympic National Forest, and the states of Oregon and California is presented in Figure 1. (Readers interested in a more specific comparison should consult the source documents.)

While previous T/F/W temperature studies have provided recommendations for riparian management on Type 1-3 streams, temperature concerns relative to Type 4 streams have not yet been addressed. Specifically, the possibility of temperature effects from Type 4 waters, for which riparian buffers are typically not required, on downstream, salmonid-bearing waters is a concern within T/F/W. This research project builds upon the previous findings of Sullivan and others (1990) to investigate the downstream temperature effects of Type 4 waters.

In Washington, no shading is currently required to be left after timber harvest on Type 4/5 streams, although typically some understory shade remains after logging from brush and logging debris. Recovery of shade from overstory canopy can be expected approximately 5 years or more after timber harvest (Summers, 1982). Removal of shade along Type 4 streams could potentially result in large increases in maximum temperature since small shallow streams respond rapidly to changes in heat energy exchange (Brown, 1969).

We expected Type 4 streams to show temperature regimes similar to those reported for larger streams. Observed maximum temperatures in small, open Type 3 streams studied in 1988 (Sullivan and others, 1990) ranged from 18 - 22°C. Higher elevation streams tended to be cooler than lower-elevation streams. A slightly wider range in temperatures was expected in Type 4 waters for two reasons. Type 4 streams with lower maximum temperatures were expected since incoming groundwater which is relatively cool makes up a proportionately greater amount of the total flow in smaller streams. Type 4 streams with very high groundwater inflow rates would be expected to not exceed 15°C. However, we also expected some Type 4 streams to have very high maximum temperatures since they tend to be very shallow and thus respond rapidly to diurnal air temperature fluctuations.

While many unshaded Type 4 streams could be expected to show similar temperature patterns, and to respond similarly at similar elevations as the Type 3 streams studied, the extent that these streams affect downstream, fish-bearing waters remains unclear. Since Type 4 streams within a basin tend to be at higher elevations, they are likely to be somewhat cooler than similar streams at lower altitudes. In addition, Type 4 streams are generally shallow, and make up a small volume of the total flow in downstream reaches, where riparian areas maintain cooler temperatures. However, in the headwaters of a basin, Type 4 streams make up a large proportion of the stream length. Because of these offsetting factors, the overall importance of Type 4 streams in determining downstream temperatures is uncertain.

The characterization of stream temperature regimes of Type 4 waters, and their downstream effects on Type 2/3 waters is the focus of this study.

Figure 1. Stream Classification Systems.

<table>
<tr><th>Washington</th><th>USFS: Olympic NF</th><th>Oregon</th><th>California</th><th>Stream Orders</th></tr>
<tr><td rowspan="2">Type 1</td><td rowspan="4">Class I</td><td rowspan="5">Class I</td><td rowspan="4">Class I</td><td rowspan="2">Fifth</td></tr>
<tr></tr>
<tr><td rowspan="2">Type 2</td><td rowspan="2">Fourth</td></tr>
<tr></tr>
<tr><td rowspan="2">Type 3</td><td rowspan="2">Class II</td><td rowspan="3">Class 2</td><td rowspan="2">Third</td></tr>
<tr><td rowspan="2">Class 2 SP</td></tr>
<tr><td rowspan="2">Type 4</td><td rowspan="2">Class III</td><td rowspan="2">Second</td></tr>
<tr><td rowspan="3">class 2</td><td rowspan="3">Class 3</td></tr>
<tr><td rowspan="2">Type 5</td><td rowspan="2">Class IV</td><td rowspan="2">First</td></tr>
<tr></tr>
</table>

Sources:

1: Washington Forest Practice Regulations, WAC 222-16-030
2 : J. Seymour, R. Stephens, USFS Olympic National Forest, pers. comm.
3 : Oregon Forest Practice Rules OAR 629-24-101
4 : California Forest Practice Rules CCR 916.5, Table 1-14
5 : Adapted from Dunne and Leopold, 1978.

Notes:

1. Oregon State stream classifications are currently under review, and will be revised by September 1992.

2. Stream characteristics (such as size and slope), as well as allowable forest practices, are not the same between all classifications listed here as similar. This table is intended to convey a general sense of comparable stream types. Readers interested in more complete comparisons should consult the source documents.

Theoretical Background

The water temperature observed at any location within a stream system reflects a balance between heat input and heat loss. The exchange of heat across the air-water interface is one of the more important factors that governs the temperature of a water body for a given solar input. The rates of both input and loss of heat are influenced by local environmental factors. Heat input is determined by the amount of direct solar radiation reaching the stream environment which varies daily and seasonally with position of the sun, and with shading by riparian vegetation or topography. Heat loss is largely regulated by the difference between air and water temperature. Conduction to the stream bed and groundwater inflow also account for heat loss.

As a stream is heated by solar radiation and convection over a daily solar cycle, heat loss from evaporation and radiation back to the sky also increases rapidly. Some stream temperature will always be reached where heat loss balances heat gain and no further change in water temperature occurs with increased energy input. Edinger and others (1968) referred to the water temperature at which heat input just balances heat loss as "equilibrium temperature". Since most of the energy exchange terms involve air temperature, this factor is very influential in determining the equilibrium stream temperature (Adams and Sullivan, 1990). Air temperature continually changes in response to varying meteorological conditions on a daily and seasonal basis and there is an equilibrium water temperature for each air temperature (Edinger and others, 1968). The water temperature is continually driven towards the air temperature with the rate determined by the difference between the two. A useful illustration of this principle is the tendency for both hot and cold water to change over a short time to match room temperature.

Importantly, rapid heat loss at high temperatures sets an upper limit to stream temperature relative to air temperature that is independent of stream size. During hot summer days when the temperature differential is greater than this amount, the heat loss from evaporation and radiation losses is also great and additional incoming heat to the water is quickly lost back to the air. Thus each stream has a maximum water temperature observed at a threshold level of air temperature. (When air temperature is lower than the threshold value, water temperature responds to it, but when air temperature rises above this level there will be no increase in the observed water temperature.) We refer to this water temperature as the "maximum equilibrium temperature."

Maximum Equilibrium Temperature: The maximum equilibrium temperature of each stream reach is independent of observed air temperature and is related primarily to the site conditions (Figure 2). Each reach's equilibrium temperature is determined by its unique combination of physical characteristics that influence stream heating. These include stream channel features (depth, width, velocity, substrate composition), riparian shading, and geographic location (latitude, elevation).

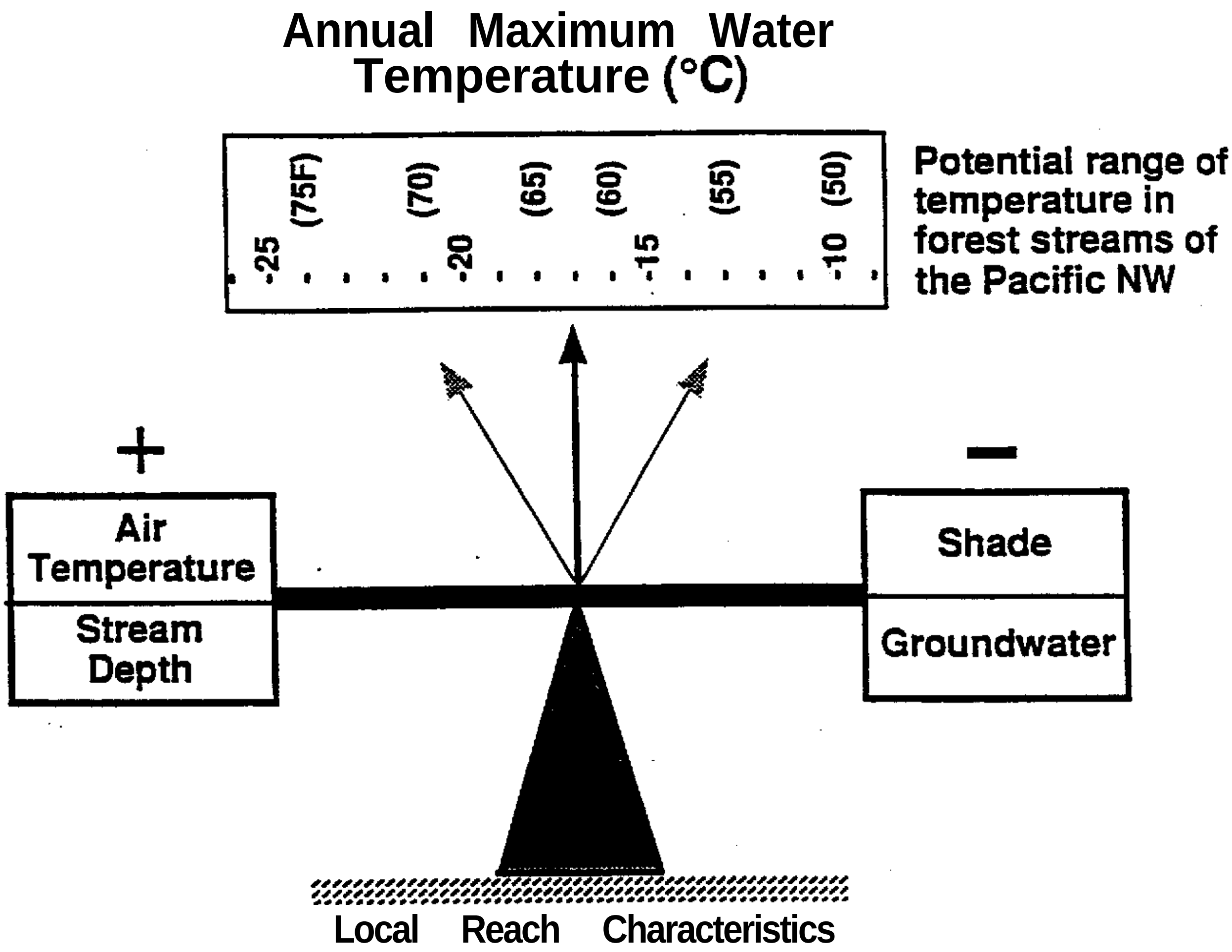


Fig 2. Maximum equilibrium water temperature for a stream reach is a function of the balance between heat energy losses and gains. High values of air temperature and stream depth tend to increase water temperature as high as approximately 25°C for Washington streams. High amounts of shade or high groundwater inflow rates will decrease the maximum equilibrium water temperature.

The numerous site characteristics contributing to the determination of stream temperature may vary inter-dependently, independently, or inversely. The maximum equilibrium temperature relates to site characteristics in identifiable, albeit complicated, ways. Nevertheless, common relationships between maximum equilibrium water temperature and site conditions exist (Sullivan and others, 1990). Changes in the local environmental conditions cause a change in the equilibrium temperature to a new value. Common responses to changes in site conditions with land use can be identified.

The annual maximum temperature is a good measure of the maximum equilibrium temperature. This temperature may not be observed frequently, depending on the climatic conditions, but it is indicative of the balance of site characteristics. Generally, the maximum equilibrium temperature in all streams and rivers will occur somewhere within the range between 9 and 25°C (48-77°F).

The 1988 - 1990 T/F/W temperature study demonstrated several other principles of stream heating at both the stream reach and basin scales. The following information summarizes some of the findings reported in Sullivan and others (1990).

Stream Reach Temperature: Stream temperature and site characteristics were evaluated to identity what features could be used to recognize streams exceeding the Washington water quality temperature criteria. A number of environmental factors were well correlated with stream temperature and several good empirical relationships between stream characteristics and water temperature were developed based on five of the most important environmental variables including stream shading, mean air temperature, elevation, stream discharge, and bankfull width. Other variables more directly influential in the physical processes of stream heating were also identified, but of the well-correlated variables those that are easiest to measure were selected. Typically, a combination of local environmental factors had an important influence on water temperature, but no one factor alone was a good predictor of stream temperature.

Baseline Maximum Temperature: The temperatures within reaches flowing through mature forests were evaluated to estimate the expected baseline maximum equilibrium temperatures within watersheds fully forested with mature conifers. Sullivan and others (1990) used measured values of maximum daily temperature during the warmest summer period of approximately 20 forested stream reaches of all sixes to draw the relationship between maximum water temperature and increasing stream size (indexed as distance downstream from the watershed divide) shown in Figure 3. This graph depicts the best estimate of baseline maximum daily temperature within fully forested Washington watersheds available at present.

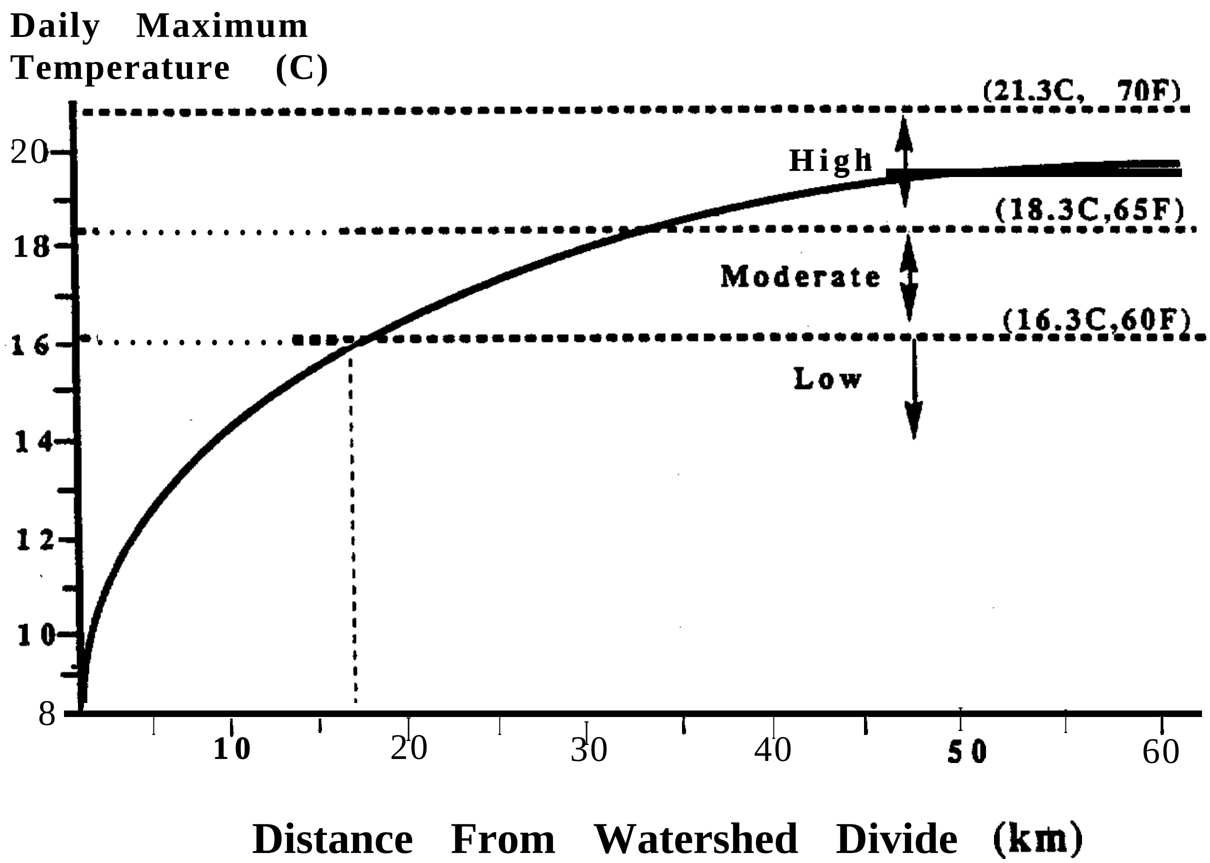


Fig. 3 Baseline Maximum Temperatures. Estimated baseline daily maximum temperature during the warmest summer days under a mature forest canopy as a function of distance from watershed divide.

Small streams relatively close to the watershed divide tend to be very cool (between 10 and 14°C or 50-56°F) with the smallest streams near groundwater temperature. (This represents the minimum possible summer temperature.) Stream reaches within forested riparian zones located approximately 20 or more kilometers (12 miles) downstream from the watershed divide are likely to exceed 16.3°C (62°F). Those sites greater than 50-60 km (30-40 miles) from divide are likely to exceed 18.3°C (65°F) during the warmest periods of the year, regardless of forest management activities upstream. Local deviations in this general trend can occur such as where cooler or warmer tributaries join the system, or at the interface between rivers and oceans where air temperatures may be cooler than similar elevations located inland. Therefore, the baseline maximum temperature in Figure 3 should be considered a rule-of-thumb and can vary with local conditions. Regional validation of this relationship would be useful.

Response Distance: Sullivan and others (1990) calculated that temperature equilrbrium was established in 600 meters or less for Type 3 streams. (Stream sixes reported in that study ranged in depth from 0.07 m to 0.6 m and in width from 0.6 - 22.8 m.) This estimate was based on a theoretical understanding of the heat exchange processes in streams and water stream flow velocities. The distance required for streams to reach equihbrium has not been empirically validated.

The concept of temperature equilrbrium is important to understanding basin temperature effects. Small streams are expected to heat quickly (i.e., within minutes to several hours) with a reduction in shade. Canopy removal should establish a new elevated equilibrium temperature for that reach. As the water enters a downstream reach with shade, it will quickly cool to the equilibrium temperature of the downstream reach. The exact length of stream required to reach equihbrium has not yet been determined but probably varies from several hundred meters in small streams to several kilometers for large rivers. Similarly, a small shaded stream is expected to be cooler relative to a downstream reach with reduced shade. However, as the stream flows through the downstream reach, the water will reach equihbrium with surrounding conditions, and the effect of the initially cooler upstream water will no longer be felt. The response times of small streams determines the extent of downstream impacts of upstream riparian management decisions.

The response time, or response distance, is defined in this study as the time required by a Type 2/3 stream to reach temperature equilibrium following the introduction of water at a different temperature from incoming Type 4 waters. This response time can be equated with the downstream distance needed to reach equilibrium (response time * water velocity = equihbrium distance). From a management perspective the equilrbrium distance defines the downstream area that a temperature response to riparian alteration can be detected.

III. Study Objectives

The objectives of this study are as follows.

1. Characterize temperature regimes and important channel characteristics which influence stream temperatures, and response to management related changes, of Type 4 waters in Washington. We hypothesize that stream temperatures in these smaller streams respond according to the same physical principles and conditions as previously reported for larger streams (Sullivan and others, 1990).

2. Determine the downstream zone of influence within salmonid bearing waters that results from shade canopy removal along upstream Type 4 waters. Both the magnitude and the total stream distance affected till be investigated.

3. Assist the Water Quality Steering Committee regarding management recommendations on downstream temperature effects, if any, of current regulations for Type 4 streams.

IV Methods

Water Types

Type 4 and 5 waters, defined in the Washington Forest Practices Rules and Regulations (WAC 222-16-030), are small headwater streams that do not support significant fish populations, are not developed water supplies, and are of importance in protecting water quality downstream. An upper limit on the size of Type 4 stream channels is 5-10 feet wide at ordinary high water (depending on the species of fish that have access to the stream), and the lower limit is 2 feet wide. Type 4 streams have a minimum summer flow less than 0.009 cubic meters per second (0.3 cfs), while Type 5 waters are defined as areas not designated Types l-4 and include intermittent streams. Type 4 and 5 waters correspond to zero order, first order, second order, and small third order streams (MacDonald and Ritland, 1989).

Land units containing Type 4 and 5 waters are subject to a number of regulations on forest practices and harvesting, such as the requirements to buffer the stream from road sedimentation, and to minimize skidding timber across Type 4 stream channels. However, streamside strips of trees and other vegetation, or Riparian Management Zones, are required on Types 1-3 waters, and are typically not required on Types 4 & 5 stream reaches.

Assumptions

This study's approach to site selection and data analysis methods rested on several assumptions. This study focused on the downstream temperature effects from harvest practices on Type 4 waters. We assumed that temperature concerns for, larger Washington streams were addressed by other studies (Sullivan and others, 1990). Type 5 waters were not eliminated from consideration, but also were not emphasized since they typically have only minimal flows during the warmest part of the year, and thus are typically too small to affect downstream temperatures. The identification of Type 4 streams was based on the definitions in the Forest Practices Manual (1988), as well as available Department of Natural Resources Water Type maps. When information was available from local foresters, recent changes in water typing of stream reaches was incorporated. When other information was not available, we assumed that the boundary between Type 4 and Type 3 reaches coincided with the start of a streamside buffer area or the edge of an unharvested unit.

We also assumed that the same physical principles of heat exchange that determine stream temperatures in Type 1-3 streams (Sullivan and others, 1990) also operate in smaller streams. These principles have been extensively studied and are well understood (Edinger and others, 1968; Theurer and others, 1974). A brief description of the important physical heat exchange processes is presented in section II of this report.

Stream discharge was assumed to be constant over the short late-summer monitoring periods. The stream flow was measured either once during the monitoring period, or calculated as the average of flows measured at the beginning and end of the monitoring period.

Even though all of the instruments used are capable of precision within 0.3°C and instrument accuracy was verified prior to their use, only differences in measured temperature greater than 0.5°C were considered significant.

We also assumed that Type 4 streams with total harvest of the overhead canopy were of primary concern within T/F/W. The most extreme temperature impacts would be associated with total riparian removal. Se sought harvested Type 4's flowing into shaded Type 3 streams since it was assumed that, with time, the new T/F/W regulations would provide adequate shade on all Type l-3 waters whereas buffers on Type 4 streams are not routinely mandatory.

Studv Site Selection

Candidate study sites were evaluated on several criteria, defined by the hypothesis being tested. First, both Type 3 and 4 stream reaches needed to be adequately long (to have reached equilibrium temperature), on the order of 460 meters. Study sites were chosen to represent as wide a range of stream characteristics such as shade levels, stream sizes, geographic distribution and elevation as possible. Priority was placed on Type 4 stream reaches where area on both sides of the stream had been harvested, not one side only. Finally, practicality was considered with regard to site accessibility and budget constraints. Unfortunately, this last factor precluded the opportunity to include study sites in ail ecoregions of the state.

Shade characteristics were a primary consideration in site selection. Three site configuration situations were sought. These included:

1. A Type 4 stream, after harvest, flowing into a Type 3 stream with a riparian zone or a Type 3 with a mature canopy cover.

2. A shaded Type 4 stream, with relatively cool temperatures, flowing into a warmer Type 3 stream.

3. A harvested Type 4 stream that had suffered a dam-break flood event, flowing into a Type 3 stream with a riparian zone or a mature canopy cover.

Both site configurations where the Type 4 stream was a tributary to the Type 3, as well as where the single stream channel crossed the 4/3 boundary were sought. Sites on harvest units within 2-4 years of harvesting were targeted, since significant shading from understory plants and replanted trees could be assumed to be present 5 years after harvest.
In addition to shade, the stream flow geometry was important for site selection. Streams with beaver ponds, intermittent surface flow, or an undefined stream channel were

eliminated as candidate sites due to the complexity of descniing the groundwater interactions.

Site selection required that the channel characteristics, including shade levels, of the downstream Type 3 water be uniform for a sufficient length to allow the stream to reach equilibrium. Furthermore, in the case of a confluence of a Type 4 and a Type 3 stream, the Type 3 stream reach had to be in equilibrium upstream of the confluence for at least 460 meters. In the case of a Type 4 stream crossing into a forested zone, the upstream reach also needed to have a homogenous shading level for at least 460 m.

The size of the Type 4 stream relative to the Type 3 stream was also an important consideration. Where a Type 4 stream joins a Type 3 stream, its discharge must be large enough relative to the receiving Type 3 stream to be capable of influencing the temperature of the downstream reach. This constraint limited candidate sites to those where the downstream waters were smaller Type 3 streams. Type 1 & 2 waters are too large, by definition, to be affected by a stream as small as a Type 4. The size of receiving waters needed at candidate sites was calculated using the flow mixing equation described below.

<u>Stream Flow Mixing</u>

Two types of stream configurations were studied; Type 4 streams converting to a downstream Type 3 reach, and a Type 4 stream joining a Type 3 stream. In the latter case, a simple mixing equation (Brown, 1969) was used to both verify the size of Type 4 streams needed to influence the receiving Type 3 stream enough to cause a measurable difference in stream temperature immediately below the confluence. The mixing equation is as follows. T_1 and Q_1 equal the temperature and stream flow, respectively, for inflowing Type 4 stream and T_2 and Q_2 represent the same values for the Type 3 stream.

$$\frac{(T_1 * Q_1) + (T_2 * Q_2)}{Q_1 + Q_2}$$

Figure 4 provides an example of the influence of incoming water at a different temperature. For example, if the incoming tniutary temperature is 20°C and has 20% the discharge of the receiving stream, which is at 12°C, then the resulting temperature when the two streams mix is 14°C.

Using this equation, and a range of theoretical Type 4 incoming stream temperatures, we estimated that the Type 4 stream would need to be at least 10% of the Type 3 stream's size in order to influence its temperature. This limited site selection to the smaller Type 3 streams, and eliminated many Type 4 candidates as too small.

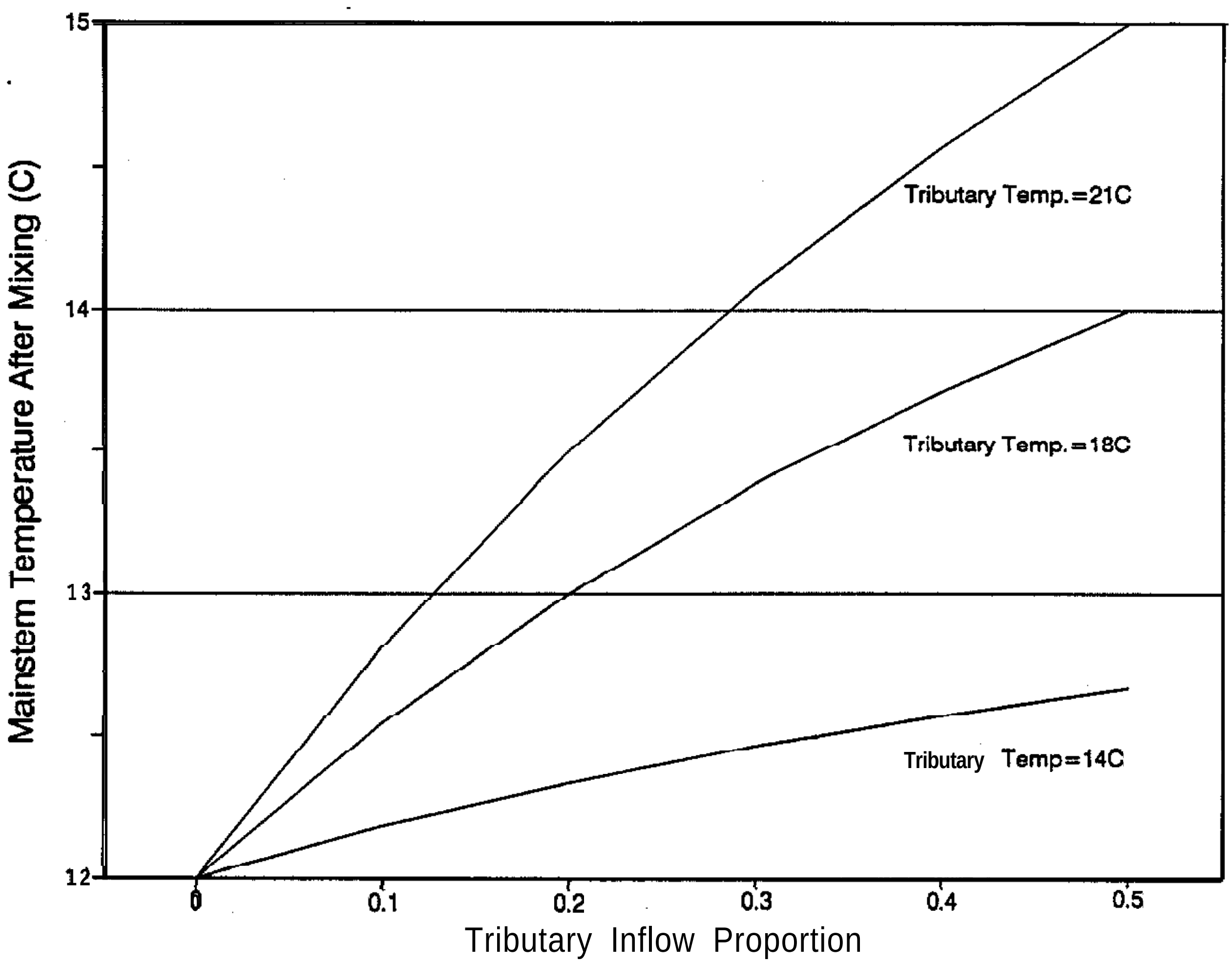


Figure 4. Temperature effects of tributary mixing. The mainstream temperature upstream of the confluence is assumed to be 12 degrees celcius. The influence on the downstream temperature is shown for incoming tributaries of three different temperatures.

Temoerature Measurement

At each site, thermographs were set out according to site configuration. Temperatures were measured in the Type 4 waters, and in the Type 3 waters upstream and downstream of the confluence with the Type 4. Temperature was also measured at regular points downstream, within the projected zone of influence from the Type 4 stream, as well as downstream of the projected return to equilibrium of the Type 3 stream. For both Type 3 and Type 4 streams, riparian conditions upstream of the thermograph were homogeneous for at least 460 m. Moving downstream in the Type 3 stream, conditions were chosen either to be homogeneous throughout the instrumented reach, or at least were homogeneous for the most downstream 460 m of the instrumented reach. Figure 5 shows study site locations, and Figures 6 - 13 illustrate actual instrument deployment.

After a suitable site was identified, calibrated continuous-recording thermographs were installed at several measuring points within each study site. A combination of Omnidata^{tm}, Unidata^{tm}, and Ryan^{tm} instruments were used. Air and water temperatures were measured every ten minutes, and recorded hourly. (A list of temperature instruments used and their estimated accuracy is in Table 1.) Water temperatures were measured at all measuring points, and air temperatures were measured where necessary (for instance, redundant air temperature measurements of the same Type 3 riparian conditions were not made.) Instrument probes were placed in the central flow of the channel. Air temperature probes were placed as close to the stream as possible, and shaded from direct sunlight. Sites were monitored for a minimum of two consecutive weeks between July and early September, 1990.

Table 1. Instrument Accuracy

Omnidata Datapod DP212	$\pm$ 0.2% of reading[1]
Unidata 6507A	$\pm$ 0.2 degrees C[2]
Ryan Tempmentor RTM	$\pm$ 0.2 degrees C[3]

1. Omnidata Intl., 1982. DP212 Operating Manual.
2. Unidata America, 1987. Starlog Portable Data Logger Product Catalog.
3. Ryan Instruments, 1990. Ryan Tempmentor Calibration Certification Sheets.

For all measurement points, instantaneous thermograph measurementswere checked against hand-held thermometer measurements made at the time of installation, removal, and during the site characterization visit.

Site Characterization

At each site, for each homogenous stream reach, an array of site characteristics were measured. These included stream width, depth, and amount of flow, as well as substrate character, channel characteristics, water velocity (for Type 3 streams), riparian shade levels, stream azimuth and site altitude. Stream width and depth were calculated by averaging 4 - 9 randomly selected measurements between each thermograph measuring point, using a hip chain, a tape or a calibrated wading rod. Distances were measured using a hip chain. Canopy shading was calculated using a forest densiometer, while shading from understory plants and logging debris at ground level was estimated visually. Shading measurements were also made by averaging 4 - 9 measurements. Water velocity was determined by timing the movement of a small amount of tracer dye a measured distance downstream. Stream flow was measured with a Swoffer™ velocity meter and top-set wading rod. Visual descriptions were made of forest type and age, as well as riparian vegetation and overall site characteristics. Sites were mapped and documentary photographs were taken.

Stream azimuths and gradients were determined using USGS maps, and any unmeasured distances between measuring points were determined using maps and aerial photographs.

Data Analysis

Temperature data was downloaded from the thermographs to personal computers, and checked for quality prior to transferring data to a mainframe computer for data processing. Hourly air and water measurements were summarized into files containing daily maximum, mean, and minimum temperatures. For each site, daily air and water temperatures were graphed over time, to estimate equilibrium temperature regimes at each site. Typical temperature regimes of the Type 4 and 3 streams were analyzed. Data analysis focussed on maximum temperatures for two reasons. First, forest practices regulation are primarily concerned with maximum temperatures. Second, the maximum equilibrium temperature is predominantly a function of site conditions, unlike the mean water temperature, which is more closely related to climatic conditions. The temperatures at each site were analyzed with regard to site configuration, to see if downstream effects of the Type 4 waters could be identified.

For site configurations where the Type 4 stream was a tributary to the Type 3 stream, the mixing equation was used to see if the observed temperatures downstream of the confluence differed from that predicted by the mixing equation. If the stream temperature calculated by the mixing equation did not differ from that observed in the Type 3 stream above the confluence with the Type 4 stream, mixing was considered to be instantaneous, and the Type 4 stream was considered to have no downstream effect on water temperatures in the Type 3 reach. If a temperature difference was seen downstream, then a zone of influence of the Type 4 was determined to be present. (Temperatures within 0.5 °C were considered not to be different from one another.)

For site configurations where the water type changed from 4 to 3 in a single stream channel, maximum temperatures were evaluated with regard to their distance downstream of the change in riparian shade, to investigate the response distance of the stream temperature to the new riparian configuration. Analysis was done on a site-by-site basis, with attention to any changes in stream or channel characteristics that might explain an observed temperature change.

V Results

Site Candidate Search

Despite a large number of suggestions from T/F/W co-operators, and a search effort covering many forested areas of Ring, Whatcom, Skagit, Snohomish, Clallam, Pierce, Thurston, Lewis, Grays Harbor, Pacific and Cowlitz counties, good site candidates proved surprisingly difficult to find.

Most of this difficulty lay in the stringent criteria we had developed, which we hypothesized to be necessary in order to document what we felt would be the worst case scenarios of downstream temperature effects of Type 4 waters. Our target criteria, which were not always met, included:

- a Type 4 stream with flow at least 15% of the size of the receiving Type 3 stream flow.
- stream crossing a land unit less than five years after timber harvest.
- both Type 4 and Type 3 reaches to be homogeneous with respect to channel and riparian characteristics for approximately 460 m upstream of their confluence, or the start of the riparian zone (for Type 4's changing to Type 3's).

The most common disqualifying factor was that the candidate Type 4 stream flowed into a Type 3 stream much larger than itself. Our target that the tributary must be close to 15% of the size of the stream it flowed into eliminated most Type 4 candidates, because their receiving Type 3 water was too large. This criteria was based on the theoretical potential of a Type 4 stream to affect temperatures in the larger downstream Type 3 reach. Many of the Type 3 streams were contained flows of 0.056 - 0.11 cms, and some as much as 0.34 cms. Most of the Type 4 streams were much smaller than the 0.009 cms upper limit in the regulations, with flows on the order of 0.003 cms, much lower than the 15% size criteria.

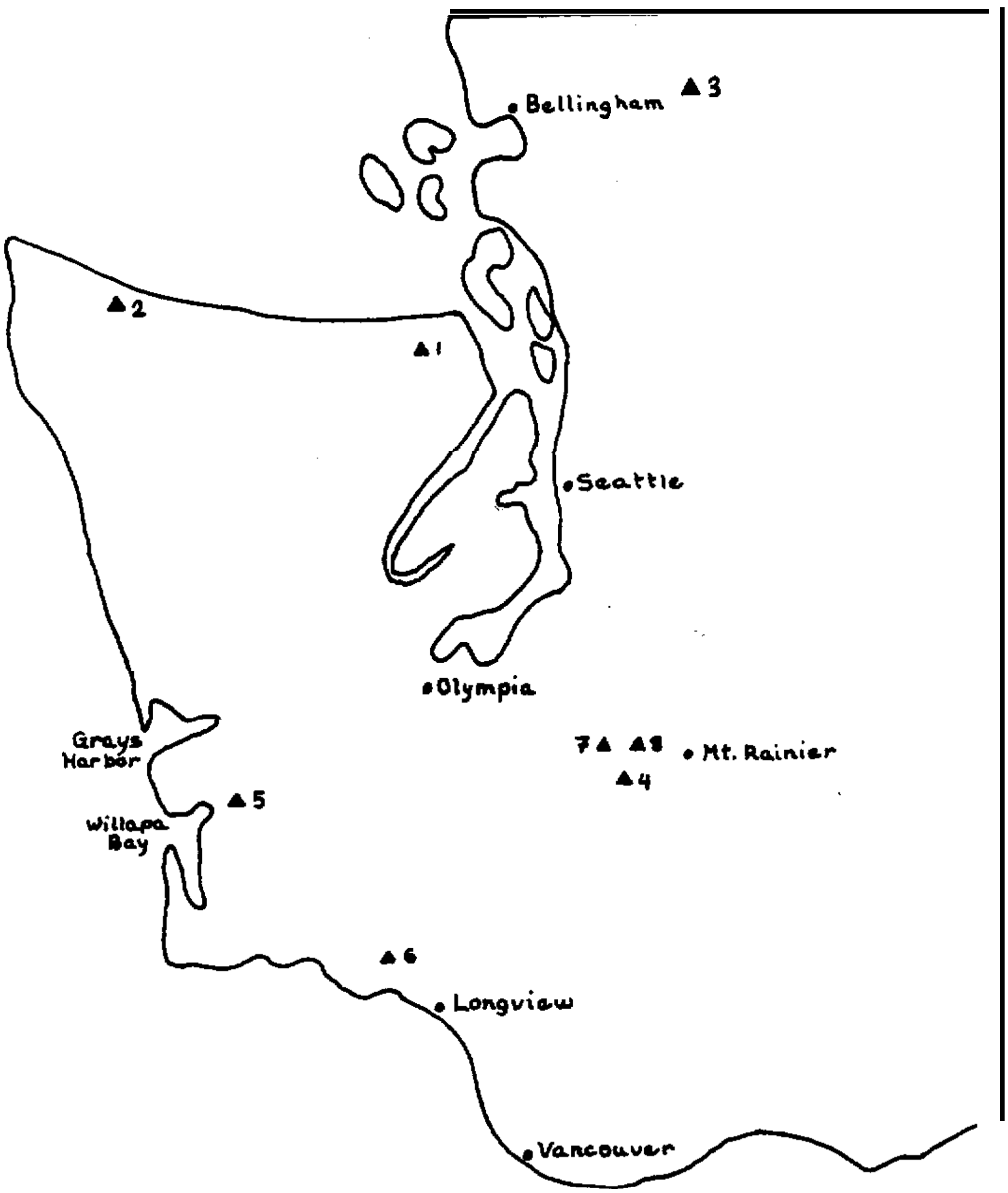
Some of the difficulty in finding sites lay in the transitory nature of the conditions we were investigating. We were looking for land units less than five years from harvest (to minimize compensating shading effects from replanted trees and understory plants). Several sites were also rejected because active falling and yarding were taking place, for safety and because we could not assume that the stream conditions were in equilibrium.

Another common disqualifying factor was the relatively large number of Type 4 streams that moved from surface to subsurface flow in part of the proposed study reach, or flowed into small beaver ponds or forest wetlands at the 4/3 boundary. Further sites were eliminated because the Type 3 stream could not be assumed to be in equilibrium, due to changes in riparian vegetation patterns below the Type 4 confluence. Another class of sites we investigated were those where both the Type 4 stream and the downstream Type 3 had suffered a dam-break flood or debris flow event. Most of these candidates were disqualified either because there was no shade on the Type 3 stream reach, or because there was no homogeneity to the Type 3 stream's riparian character.

Also, in some cases we found that land managers were leaving vegetation buffer strips on larger Type 4 streams. Since we were targeting on the larger streams (because of the relative size requirement), a number of possible candidates were disqualified because the stream reach had canopy-level riparian shade.

In summary, the investigators found that, under the new regulations and practices within T/F/W, while there are a number of Type 4 streams in any given basin, they are also very small, particularly in relation to their receiving streams. It appears that riparian buffers are voluntarily being left on many of those west side Type 4 streams which may be large enough to exert a downstream temperature influence.

Fig. 5 Site Vicinity Map
1990 T/F/W Type 4/5 Stream Temperature Study



Site Key

1’ Jimmy Come Lately Creek
2 Green Creek
3 Hoff Creek
4 Hanaford Creek
5 Ward Creek
6 Abernathy Creek
7 Huckleberry Creek
8 Thorn Creek

With respect to minimum water temperatures the only thermograph to differ from the others was the most upstream thermograph (A) located in the shaded portion of the Type 4. Point (A) minimum daily water temperatures averaged 13.2°C while minimum daily temperatures for the other thermographs averaged 12.5°C.

Although the establishment of equilibrium conditions within uniform stream reaches cannot be concluded from Figure 7, a comparison of all daily maximum temperatures between thermographs demonstrates that equilibrium conditions did exist within the Type 4 harvested reach. The mean difference in daily maximum temperatures between the two thermographs placed in the harvested Type 4 stream reach was only 0.05°C whereas these two thermographs differed significantly from the measurements at the upstream thermograph in the shaded section of the Type 4 stream.

The shade level varied between the two reaches within the Type 3 section so that a comparison of temperatures between the two monitoring points is inconclusive with regards to the establishment of equilibrium temperature regimes. It is probable that each of the two Type 3 stream reaches had unique equilibrium temperatures associated with their respective shade levels.

In conclusion, Jimmy Come Lately Creek increased in temperature within the unshaded Type 4. Stream temperatures decreased within 150 meters upon entering the downstream shaded Type 3 reach. The careful selection of trees for harvest along the Type 3 provided adequate shade to protect stream temperatures.

Green Creek

Characterization

The study site on Green Creek, a tributary to the Pysht River on the Olympic Peninsula, included a harvested Type 4 stream flowing into Green Creek, which is a Type 3 stream with a substantial riparian zone (figure 8). The Type 4 stream had only 5% canopy shade. However, understory plants and logging debris in the channel provided an average of 90% shade in the Type 4 reach. The Type 3 averaged 85% canopy shade in the study reach. (Water typing was confirmed from recent forest practices applications.)

The measured streamflow in the Type 4 reach at its mouth was 0.002 cms, and the Type 3 stream above the confluence had a flow of 0.008 cms. (Streamflow was measured both at the beginning and the end of the monitoring period, and the two measurements averaged.) The Type 4 had a moderate gradient and mostly cobble substrate. The Type 3 stream was a low gradient stream, with numerous pools. Substrate is primarily gravel and cobble with occasional bedrock outcrops.

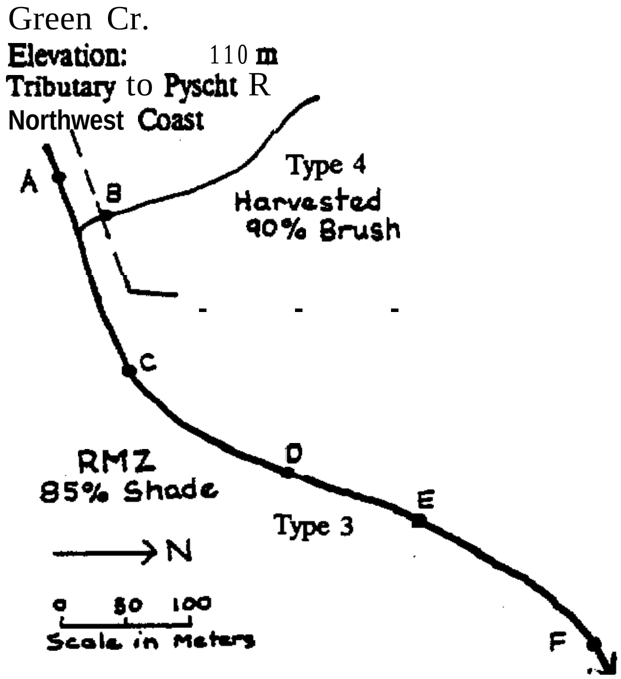
Results

The site on Green Creek was monitored from August 16 through September 10, 1991. Maximum stream temperatures were recorded on August 20. Although the overhead canopy was completely removed from the Type 4 reach for its entire length of 610 meters, it remained cool relative to the heavily canopied Green Creek. The water temperature in the Type 3 stream was reduced by 0.5°C from 17.8°C above the confluence with the introduction of the cooler Type 4 stream entering at 15.7°C. Measured temperatures were consistent with those predicted from the mixing equation. The maximum temperature for all of the monitoring stations downstream of the confluence showed little variation with all maximum temperatures for August 20 being between 17.3°C - 17.0°C; indicating the stream was in equilibrium with the conditions within this reach. Figure 8 displays maximum temperatures for the monitoring points on Green Creek.

Minimum daily temperatures during the monitoring period did not differ significantly between the six monitoring points and averaged 13.0°C.

Discussion

Cool temperatures were maintained in the Type 4 tributary due to understory plants and logging debris, which provided an average of 90% shade. A high proportion of groundwater in the total streamflow also probably contributed to the cool temperatures recorded in the Type 4 stream.



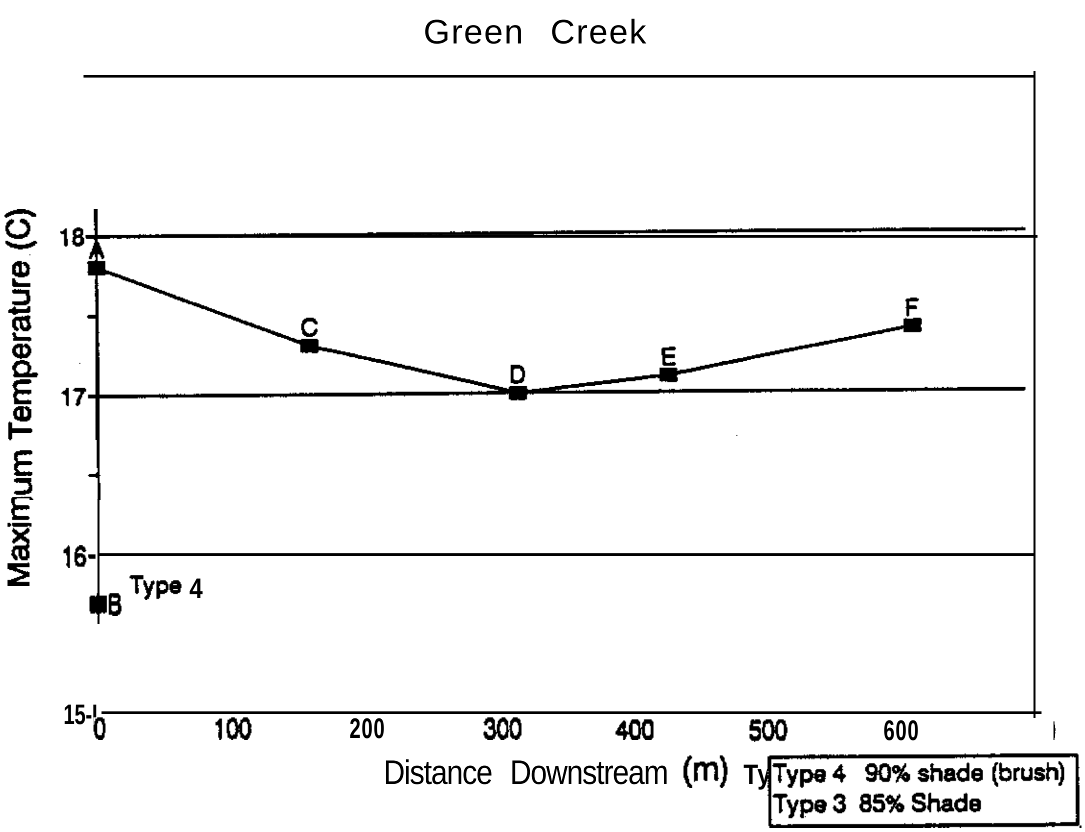


Figure 8. Green Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Although the Type 4 tributary comprised 20% of the flow of Green Creek upstream of their confluence and was substantially cooler, little effect was noted immediately downstream. The moderately high temperatures in the shaded Type 3 stream both above and below the Type 4 confluence are a function of the site's elevation and shade. The maximum temperature of 17°C is consistent with those predicted by equations presented in Sullivan and others (1990).

Ward Creek Tributary

Characterization

This study site was situated on a small tributary to Ward Creek, a low-elevation (12 m) coastal tributary to the Willapa River in southern coastal Washington (Figure 9). (Ward Creek Tributary enters Ward Creek near the confluence of Ward and Fairchild Creeks.) The upper section of the Type 4 reach of Ward Creek contained an older harvested area, perhaps 4-5 years old and not replanted except by volunteer grasses, and another section that had been harvested during the summer of 1990. Approximately 80% of the triiutary watershed was in the newly harvested area, although the lower 150 m of stream in the open zone was in the older section, with logging debris and grasses covering the stream. The low-gradient Type 4 reach (approximately 2%) entered a mature alder forest, with almost no gradient, a meandering stream channel, and extensive streambank cover from devils' club and other brush. Streamflows were too low to measure with available equipment, and were estimated to be 0.0028 - 0.007 cms. The Type 4 reach had 90% shade provided by brush but minimal overhead canopy. The Type 3 reach had 95% canopy shade.

Site configuration included one measurement point at the lower end of the harvested reach, and three measurement points in the forested reach, extending over 223 meters of forested, meandering stream. At that point, the stream entered a swampy meadow, just above its confluence with Ward Creek.

Results

Temperatures were monitored from August 9 through August 28, 1990, with maximum temperatures observed on August 11. Maximum water temperatures at point (A) in the open section was 18°C, and dropped to 17.5°C at point (B), then to 17°C at points (C) and (D) (Figure 9). Minimum water temperatures averaged 13.5 - 14.0°C for all sites.

Air temperatures were higher in the open zone (a maximum of 27°C), than in the middle of the forested zone (a maximum of 23 - 24°C), where canopy shade levels were 95%.

Discussion

In this case, it appears that stream temperatures reached equilibrium with the new riparian conditions in 26 - 150 m downstream of which there were no temperature effects of the harvested Type 4 stream. Although temperatures in the forested zone remained high (17 - 17.5°C) they were as expected based on elevation and shade. Ward Creek is a very low elevation stream. Water temperatures at low elevation streams in Washington will be high even under mature forest canopy conditions.

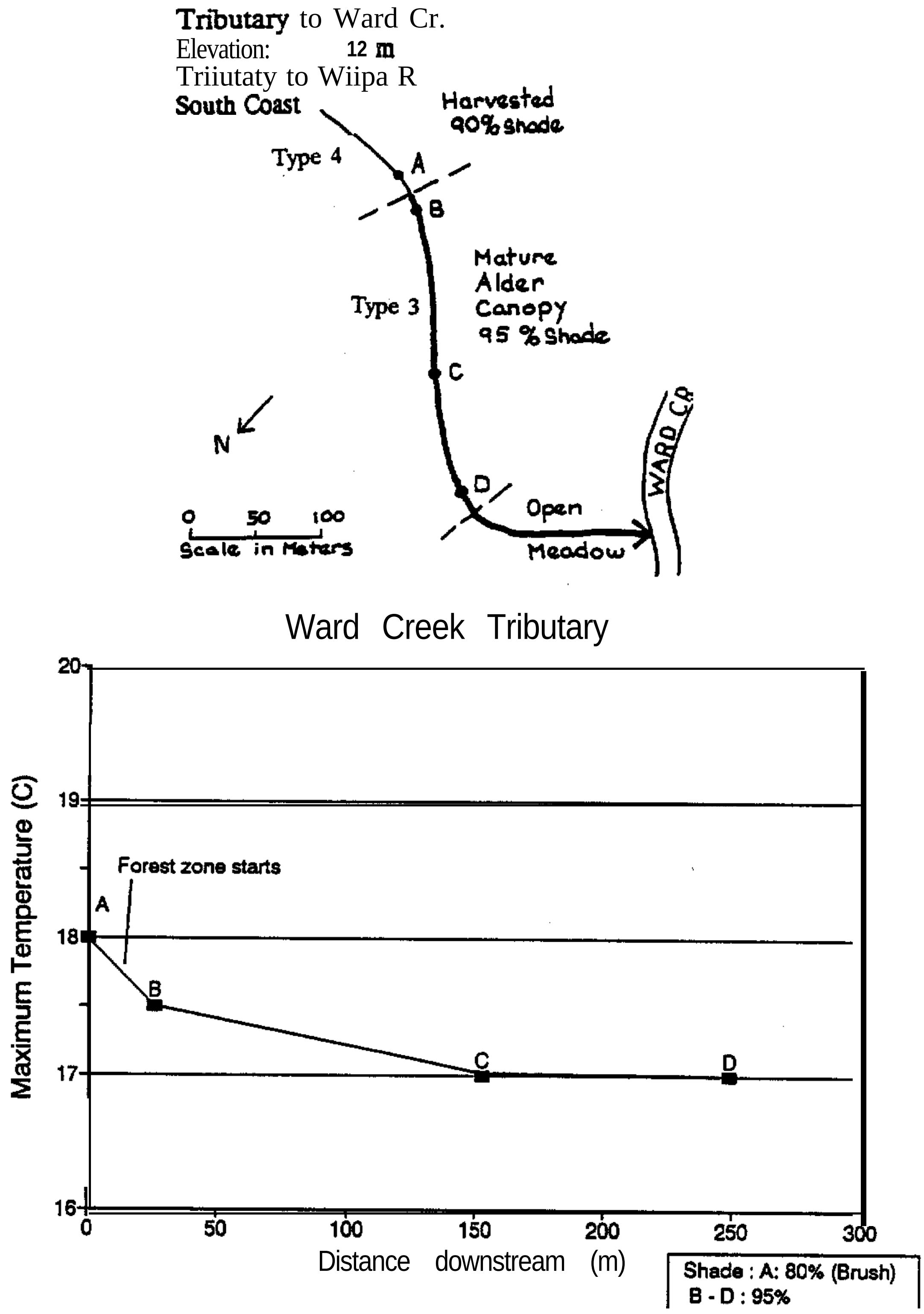


Figure 9. Ward Creek Tributary site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Huckleberry Creek

Characterization

Huckleberry Creek, a small Type 3 stream, was included in this study for two reasons. First, temperature data existed from other ongoing monitoring activities and we had relatively few other sites. Second, this stream had experienced a dam-break flood event during the winter of 1989-1990 which affected the upper end but did not alter the canopy immediately downstream. Despite the fact that Huckleberry Creek is not regulated as a Type 4 stream for this reach it was thought that information from this site would be useful in evaluating smaller streams. (All other debris flow/ dam-break flood site candidates were unacceptable, either because the debris flow continued down the Type 3 channel, eliminating its shade, and often deposition of a large sediment wedge altered the surface expression of stream flow.)

The stream, a tributaxy to the Deschutes River in the Southern Cascades, had a site elevation of 207 m, and a flow of 0.028 cms. The most upstream measuring point was set in a meandering, braided, open channel, with a small amount of instream log debris (Figure 10). The open reach extended upstream of the measuring point at least 350 m. Below this site 150 m, the stream entered a large pile of log debris, which completely covered the channel for 125 meters. A second measuring point was set just below this logjam. Below the logjam, the stream crossed a road through a culvert, and entered an area unaffected by the dam-break flood, with a mature alder canopy, and shade levels of 90%. Two measuring points were placed in this area. Downstream of the lowest point, the stream flowed through a small residential area before its confluence with the Deschutes River. Stream gradients were approximately 3-4%.

Results

Temperatures were measured from July 27 through August 27, 1990, with maximum temperatures observed on August 12.

At point **(A),** the open stream had about 20% shading from log debris. Maximum air temperatures reached 30°C, and water temperatures reached 23°C. (The maximum water temperature was 6.7°C higher than that recorded prior to the dam break flood.) Below the logjam, at point (B), maximum air temperatures had cooled to 25°C, although it is possible that air temperatures inside the logjam were even cooler, because of the total shading. Water temperatures had cooled to 19°C below the logjam. Over the 57 meters between points (B) and (C) [the first in the forested stream zone], maximum water temperatures increased to 20.5°C. By the time the water had reached point (D), 130 m downstream from point (C), water temperatures had cooled to 19°C again, while air temperatures dropped one degree from point (C), to 26°C. Figure 11 shows maximum water temperatures observed along the study reach.

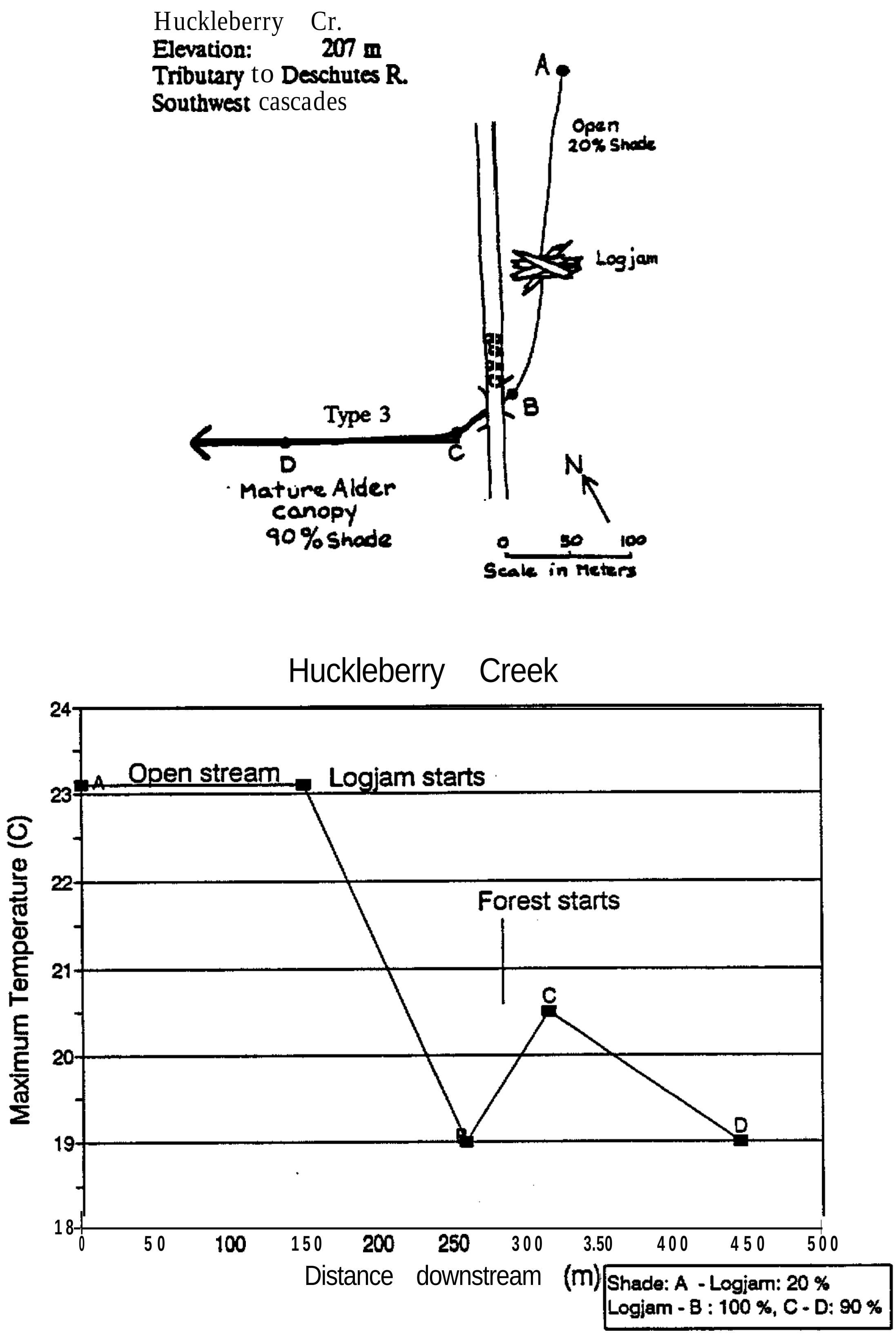


Figure 10. Huckleberry Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Discussion

Stream temperatures within the upper reach affected by the dam break flood were some of the highest recorded during this project. The lack of riparian vegetative shade resulted in high water temperatures. A 4.1°C drop in temperature occurred between point **A** and point B, the latter being inside the log jam. The rapid cooling within the log jam is due to both increased shade (100% shade in the log jam) and the possibility that the much of the stream may well have been temporarily subsurface beneath the log jam as it traversed the sediment wedge.

The 1.5°C warming in water temperature as the stream emerged from the log jam may have been an anomaly of the monitoring point within the log jam rather than a movement towards equilibrium temperature in the shaded downstream reach. One would expect a maximum equilibrium temperature of approximately 15 - 16°C based on predictive models (Sullivan and others, 1990). Although the stream continued to cool between points (C) and (D), equilibrium conditions had not yet been reached. Huckleberry Creek is larger than the other streams studied and is regulated as a Type 3 stream throughout the study reach. The greater stream depth necessitates a longer travel time for the stream to come to equilibrium. The 1.2 hours estimated travel time between point (B), in the log jam, and the most downstream point, (D), is insufficient for the stream to-reach equilibrium after the extreme temperature elevation occurring in the open reach. This larger stream would probably require another 100 m before coming into equilibrium with the shaded downstream conditions.

Hanaford Creek

Characterization

Hanaford Creek, at 280 m elevation, is a tributary to the Skookumchuck River in the Central Cascades. The main stem of the stream above two Type 4 tributaries (0.00059 cms), has a mature alder riparian zone, which is thin in some places from blow downs (33 % canopy level shade). Understory plants provide additional shade (50% brush level shade) along some sections of the study reach. Approximate stream gradient is 2-3%. Two Type 4 tributaries flow across a single large harvested unit, and join the stream 133 m from one another. Both tributaries ($8.0 * 10^{-5}$ cms and $1.0 * 10^{-4}$ cms) flow down through at least 450 m of open area before joining Hanaford Creek, with stream gradients of 6-7%. The unit had been harvested during the summer of 1990, and while yarding had occurred, some logging debris was still on the ground. The lower section of Hanaford Creek, below the tributaries, contained 70 - 85 % canopy shade (Figure 11).

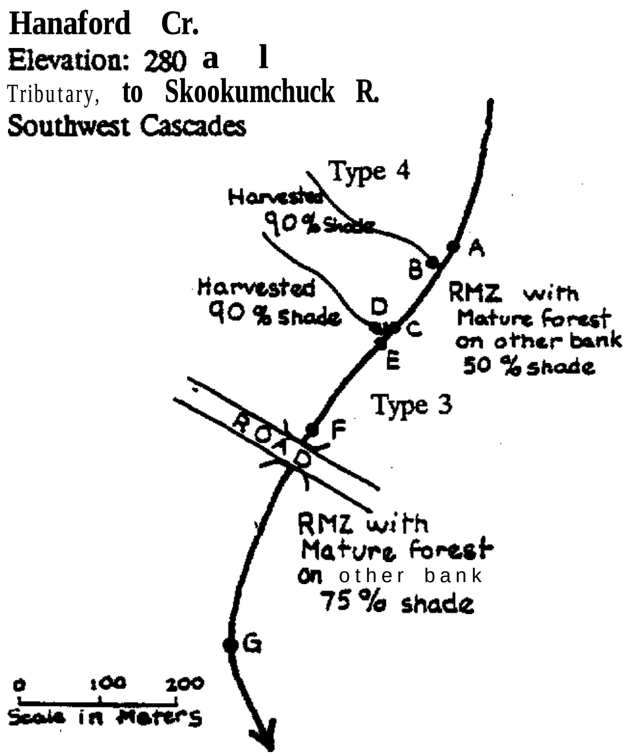
Site configuration included a measurement point above both tributaries, one just above the second triiutary, in both tributaries themselves, and three sequentially downstream with the farthest-downstream thermograph 450 m from the confluence with the lowest tributary.

Results

The monitoring period at this site was from August 10, 1990 through September 5, 1990, with the warmest temperatures observed on August 12. Maximum air temperatures were warmer in the tributaries (34°C) than at the mainstem sites, where maximum air temperatures were 29 - 31°C.

The upper tributary (B), had a maximum water temperature equal to that at point (A), in the mainstem just above it (14.5°C). Thus, there was no significant change in the maximum temperature of the main stem, seen at downstream point (C) with a maximum water temperature of 15.0°C.

The lower tributary, D, had a warmer maximum temperature (16.5°C) than point (C), just upstream of it (15.0°C). The mixing equation predicts a water temperature of 15.2 for (C) and (D) together, which equals the maximum observed temperatures of 15.0°C at both points (C) and (E). This shows that mixing of the lower tributary and the mainstem was instantaneous. The lower tributary's flow is approximately 15% of the flow in Hanaford Creek at point (C).



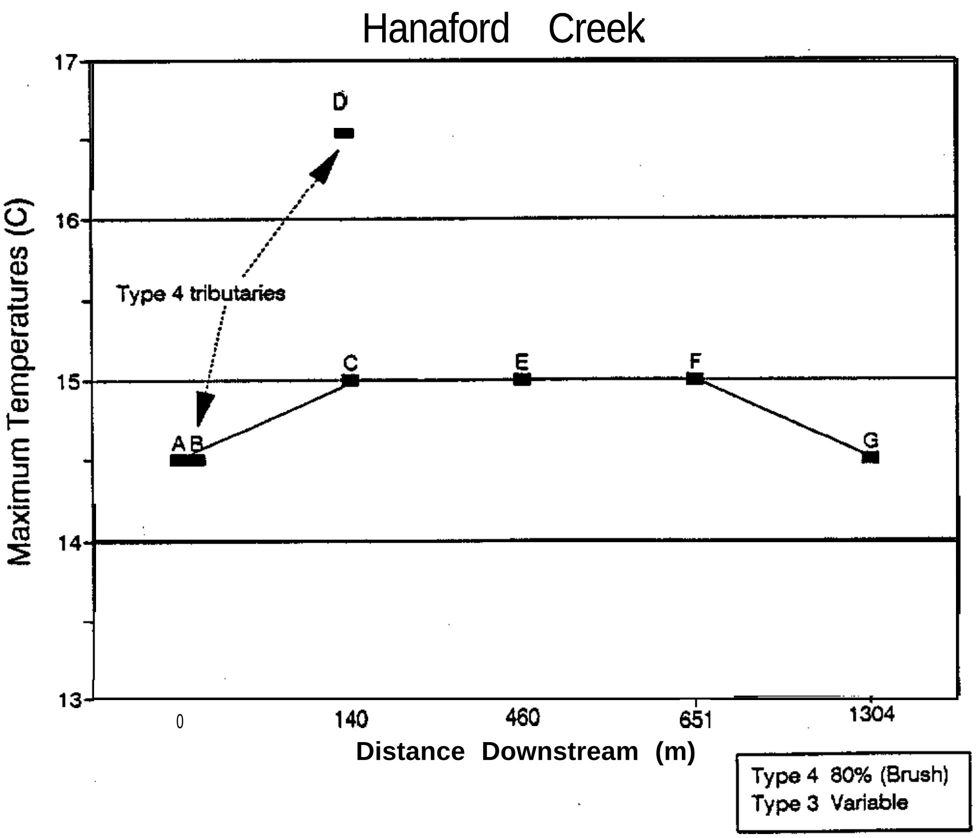


Figure 11. Hanaford Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Downstream of the confluence, maximum water temperatures in Hanaford Creek remain at 14.5 - 15°C, indicating that the stream is in equilibrium in this reach with surrounding conditions, even though canopy shade levels increase (to 70- 85%) and understory shade decreases (to 10-40%) downstream from measuring point (C) to measuring point F.

Minimum water temperatures were similar at all measuring points, averaging 12°C.

Discussion

Water temperatures in the two Type 4 tributaries are relatively cool (14.5 and 16.5°C), even though air temperatures are much warmer (maximum 34°C) in the harvested unit than in the riparian zone (maximum 29°C). This may be due to the moderate site elevation (280 m), or a high groundwater proportion of flow in the tributaries. Both Type 4 streams contained small amounts of flowing water at the top of the harvested unit, and flowed out of forested areas. In both cases, the Type 4 streams mixed immediately with the Type 3 streams at the confluence.

In the mainstem of Hanaford Creek, water temperatures remain relatively cool, even though the riparian canopy shading is thin in places resulting from blow downs. Groundwater inflow may contribute to this, as well as the high levels of shading from understory plants on some stream reaches.

The incoming Type 4 stream (lower tributary), which was warm relative to the Type 3 stream did not affect downstream temperatures. The mixing equation supports the conclusion that the difference in size between the two streams prevents any downstream temperature impact.

Thorn Creek

Characterization

The study site on Thorn Creek, a tributary to West Fork Creek and the Deschutes River in the Southwest Cascades, contains two Type 4/3 stream boundaries. The first, upper Thorn Creek, is where an open Type 4 stream reach flows into a, mature forest canopy at 580 m elevation (Figure 12). This upper unit was harvested approximately four years earlier. The stream gradient was 9%, with 0.002 cms flow. The stream then flows through a 600-meter canyon section, with a steep gradient (18%), bedrock outcrops and mature alder and conifer canopy (shade level 90%). At the end of the canyon reach, now at 457 m elevation, lower Thorn Creek is joined by another Type 4 tributary, flowing 0.0002 cms. This smaller tributary drained a replanted area approximately 4 years old, and was 20% shaded by debris in the stream. Thorn Creek then continued another 925 m, through a mixed riparian area, containing a thin alder riparian zone with some blow downs (canopy shade 25 - 40%, understory shade 60%), alternating with reaches containing uncut second-growth conifer and alder. Stream gradients in this lower reach were 10%, and the flow measured at the lowest point, 363 m elevation, was 0.012 cms.

Results

Temperatures were measured from July 18 to August 5, 1990, with the warmest temperatures observed on August 5, 1990. The daily temperatures (Appendix B) show that temperatures at all monitoring points on Thorn Creek are relatively cool, with minimal diurnal fluctuation. Figure 13, observed maximum air and water temperatures, illustrates that in spite of high air temperatures, water temperatures do not exceed approximately 14.5°C.

Minimum water temperatures ranged from 9.7 to 11.7°C for all monitoring points.

Maximum air temperature in the harvest area was 31.5°C as opposed to 26°C in the immediately adjacent forested area.

The Type 4 stream at upper Thorn Creek is moderately cool even in the open section, which has approximately 70% shading from understory plants and logging debris over the stream. Maximum water temperatures drop 0.5 degrees as the stream moves beneath an overhead canopy of shade, from measuring point (A) (open) to (B) (shaded). Further cooling is evidenced within the canyon reach, (B)-(D), where the shade is very dense; both vegetation and topography contributing. An influx of additional groundwater is also suspected in this canyon reach.

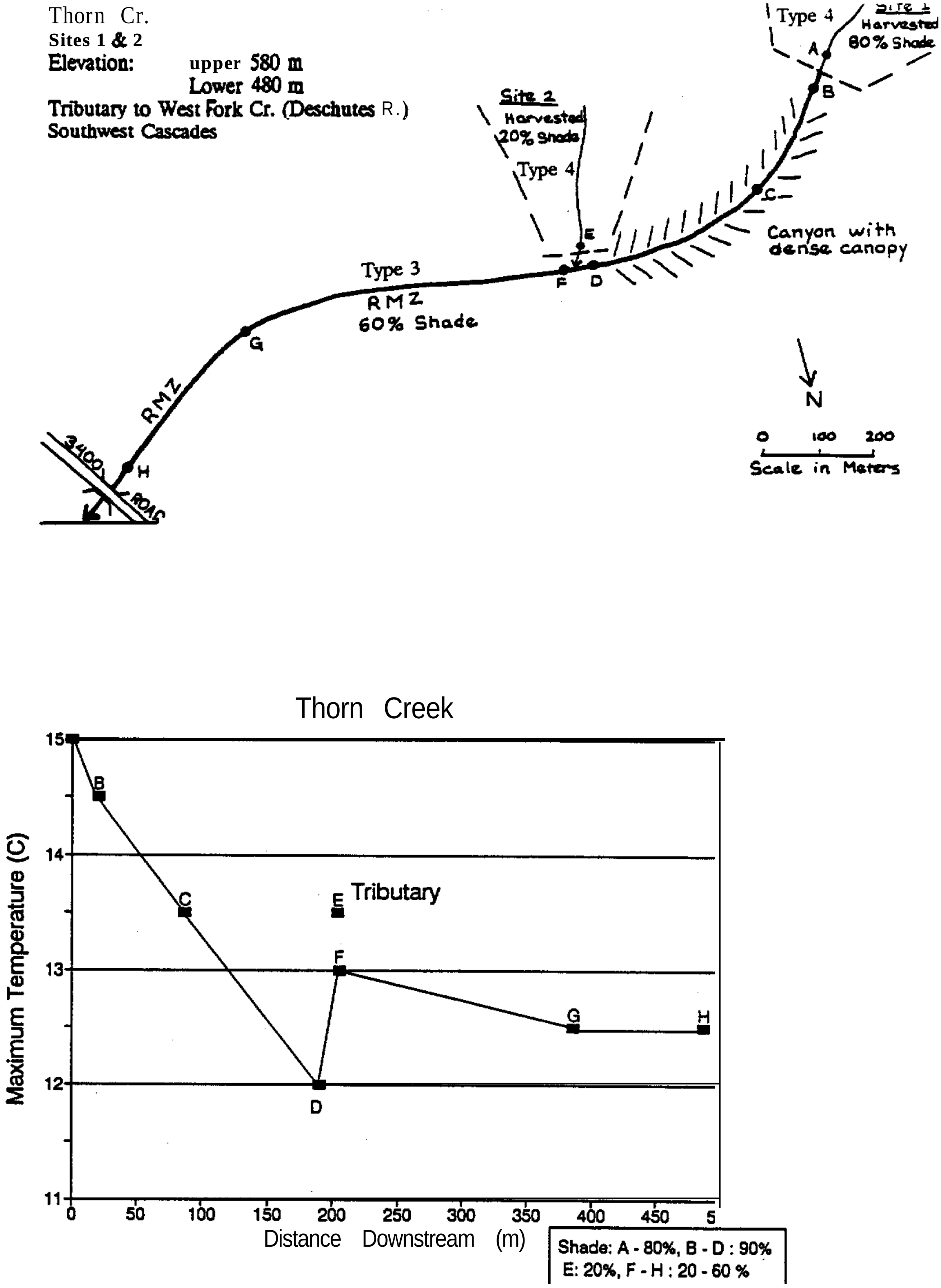


Figure 12. Thorn Creek site configuration and maximum temperatures. Locations of **thermographs** are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

At lower Thorn Creek, the stream exits the canyon reach just above measuring point (D), and a second Type 4 tributary (E) joins the stream just above measuring point (F). Maximum water temperatures at (D) are 12°C. The tributary's maximum temperature is 13.5°C, and Thorn Creek temperatures rise to 13°C at point (F), 30 meters below the confluence. The mixing equation predicts that the tributary is too small to change the temperature at point (D). Predicted mixed temperatures are 12.1°C, and observed temperatures at point (D) are 12°C. The increase in maximum temperature at point (F) is due to the stream's exit from the heavily shaded canyon reach, into a more open riparian area. This more open zone, 20-60% canopy shade, remains similar downstream for Points (F), (G) and (H), and the maximum water temperatures remain 12.5 - 13°C for all three measuring points, covering a downstream reach of 922 meters, and a drop of 95 m in elevation from (F) to (H).

Discussion

Measured temperatures are consistent with predicted temperatures for this higher elevation site. Predictive models (Sullivan and others, 1990) show that for this elevation and shade levels reported, temperatures should range between 12 - WC, depending upon shade level. In spite of high air temperatures the stream temperature did not increase beyond 14.5°C (Figure 13). This is due to the greater efficiency of the heat energy loss processes at higher elevation. The equilibrium temperature represents the balance between heat energy gains and losses. At higher elevations energy losses offset gains as rising air temperature tries to increase the stream temperature.

High groundwater rates may also have contributed to the low water temperatures at all of the monitoring points for Thorn Creek. Groundwater inflow rates (0.02 $m^3/s/km$, measured by difference in discharge) are at the high end of the range reported in Sullivan and others, 1990.

Also noteworthy is the high level of shade (70%) in the harvested reach contniuted by brush and debris. This shade also kept temperatures low within the open Type 4 stream.

At lower Thorn Creek, the mixing equation can be used to demonstrate that the inflow of the Type 4 tributary at point (E) did not significantly affect the temperature below the confluence. The increase in temperature at point (F), downstream of the confluence, is due to a new equilibrium temperature being established, within 43 meters, for the changing channel conditions as the stream exits the shaded canyon reach into a more open riparian area. The temperature predicted by the mixing equation for combining the hiiutary (point E) and the mainstem (point D) is 12.1°C, identical to the measured stream temperature at point (D). The tributary is too small to affect the downstream temperature.

The mixing equation can be further used to denionstrate the tributary did not cause the increase in temperature measured at point (F). An estimate could be made of either the size or temperature of the lower Type 4 tributary that would have to be present to change Thorn Creek's water temperature by 1°C, from 12 to 13°C. The tributary would either have to be 0.004 cms (20 times its current flow), or have a temperature of 23°C at its current size, to affect that change. A tributary of that size would exceed the upper size limit for a Type 4 stream (0.009 cms) and temperatures of that magnitude at that elevation are highly unlikely. Therefore, the lower Thorn Creek reach, like the upper Thorn Creek reach, came into equilibrium with new channel conditions in the distance between measuring points (D) and (F), 43 m. Using measured water velocities, the time for water to travel between points (D) and (F) is on the order of 0.5 hours.

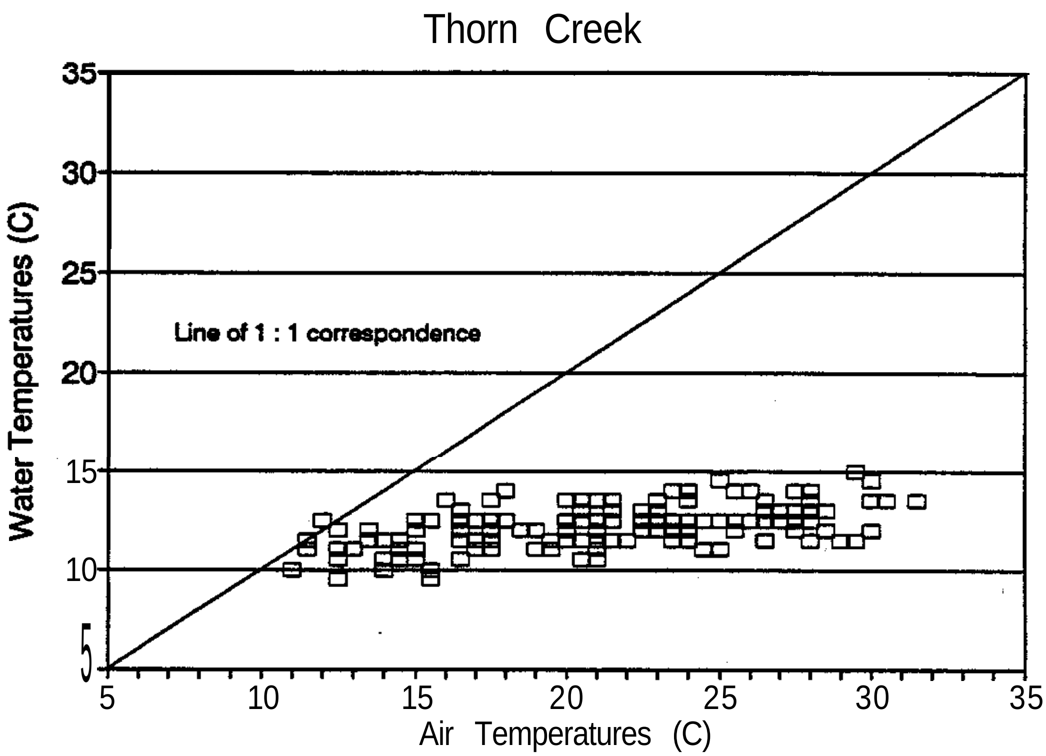


Figure 13. Maximum daily temperatures for all monitoring points on Thorn Creek. Groundwater strongly regulates stream temperatures.

Abemathv Creek

Characterization

Abernathy Creek, a small triiutary to the lower Columbia River, is a relatively large (for this study) Type 3 stream (0.14 cms) with a mature alder riparian zone (shade levels 95%). Site elevation was 195 m. A Type 4 tributary entered Abernathy Creek after crossing a harvested unit, portions of which had been harvested in 1986, and portions in 1988. The tributary stream had a gradient of 3-4%, a flow of 0.0085 cms, and a cobble channel, with approximately 80% shade from understory plants. The tributary flowed through a 66 meter wide riparian area before the confluence with Abernathy Creek (Figure 14).

Site configuration included two measurement points in the Type 4 tributary, one at the lower end of the harvest unit, and one at the lower end of the riparian area, just above the confluence. On Abernathy Creek, a measurement point was set above the confluence, one just below the confluence, and two more downstream.

The Type 4 tributary was small compared to Abernathy Creek (6% of Abernathy Creek's flow), although close to the maximum size for a Type 4 stream. It was chosen for two reasons. One was to test the hypothesis regarding necessary tributary size, and the second was to investigate the effects of a riparian area along a Type 3 reach on a warm Type 4 stream that must flow through it.

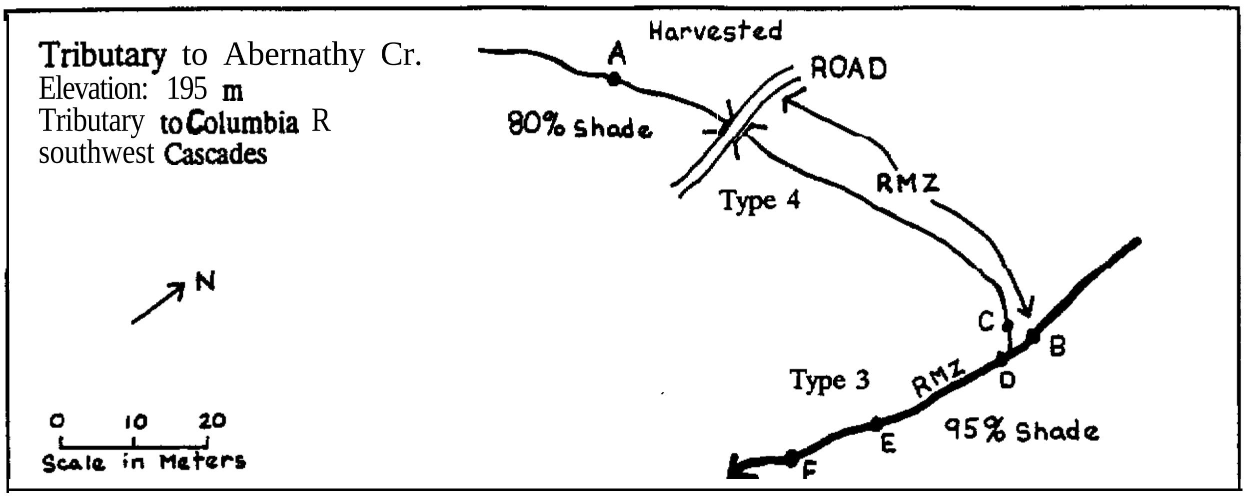
Results

Stream temperatures were measured from August 4 to August 28, with the hottest water temperatures observed on August 9, 1990.

The tributary, which had a maximum air temperature of 34°C in the open unit, and a maximum water temperature of 21.5°C, cooled as it traversed the 66 m of riparian zone. Maximum air temperatures cooled to 24.7°C, and the maximum water temperatures to 20.8°C.

Maximum water temperatures above the tributary were 18.5°C, and remained between 18.5 and 19.0°C below the confluence, and downstream. Observed temperatures were equal to those predicted by the mixing equation.

Minimum water temperatures in the Type 4 tributary were 14.9°C, while minimum temperatures in Abernathy Creek averaged 12.6°C.



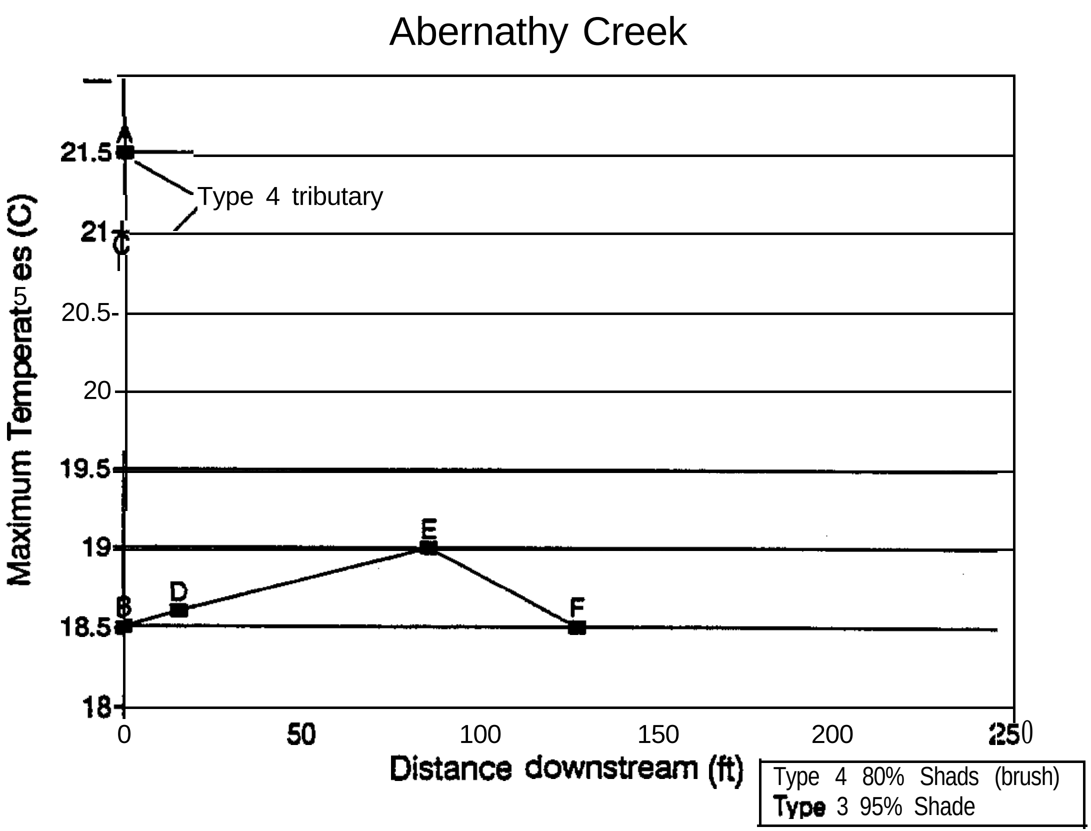


Figure 14. Abernathy Creek site configuration and maximum temperatures. Locations of thermographs are noted by their letter designation. Shade percentages may vary between thermograph monitoring points. Average shade levels for the entire reach are shown.

Discussion

Since water temperatures did not change in Abernathy Creek below the confluence with the tributary, mixing occurred between the tributary confluence and measuring point (D), 5 m downstream. This supports the hypothesis that the tributary was too small in size to influence the temperature of Abernathy Creek, which is in equilibrium with its own channel conditions. The riparian zone did reduce the tributary's maximum water temperature, probably due to the 10°C drop in maximum air temperature.

Using the mixing equation, an estimate can be made of either the size or temperature of the Type 4 tniutary that would have to be present to change Abernathy Creek's water temperature upward by 1°C, from 18.5 to 19.5°C. The tniutary would either have to be 0.113 cms in size (43% of the combined flow), or have a temperature of 36.8°C at its current size, to affect that change. A hypothetical stream of that size would exceed the upper size limit for a Type 4 stream (0.009 cms), while the calculated temperature in the second case is 2.8°C higher than the maximum air temperature recorded in the harvested unit, and 15.3°C higher than maximum water temperatures recorded in the tributary.

One possible explanation for the high temperatures observed in the Type 4 tributary might be a lack of groundwater inflow. Minimum water temperatures in the tributary averaged 14.9°C, while minimum temperatures in Abernathy Creek were 12.6°C, which indicates either that the groundwater was warmer entering the tributary, or there was less groundwater inflow.

Temoerature Regimes in Harvested Tvpe 4 Waters

Temperature regimes for Type 4 waters as characterized in this report are based on a small sample of streams for which the riparian canopy had been recently harvested. Though sample size is limited, the authors believe temperature regimes observed in this study are representative of temperature regimes for Type 4 streams throughout Western Washington that cross recently harvested land units. Furthermore, temperature regimes in Type 4 streams in Eastern Washington are likely to behave in a similar manner. As discussed elsewhere in this section, the Type 4 streams function in the same manner with respect to environmental site conditions as did streams reported in Sullivan and others (1990).

Late-summer stream temperatures were monitored for a period of at least two weeks for eleven Type 4 stream reaches. Though some of these reaches existed within the same Type 4 stream, distinctive channel conditions were identified within each reach and all eleven reaches appeared to be in equilibrium. A range of site elevations, from 12 m to 580 m, and a range of western Washington climate conditions is represented. All of the sites had been harvested within the last few years, with several sites just harvested. Even immediately after harvest, high levels of understory shade were common. The understory provided an average of 60% shade for these reaches.

Figure 15 shows the average daily temperature regimes observed for the Type 4 stream reaches. Average daily maximum stream temperatures for the Type 4 sites ranged from 12.6°C - 23.1°C. The highest recorded temperature was in Huckleberry Creek, where a recent dam-break flood removed nearly all the shade. (Huckleberry Creek is regulated as a small Type 3 stream.) The next-highest temperatures were in Hoff Creek and Abernathy Creek (18.4°C). The relatively low elevations of these sites, 166 m and 200 m, most likely accounts for the high temperatures. Average daily maximums observed at all other sites ranged from 12.6°C to 16.2°C. Of these eleven recently-harvested Type 4 sites, eight met the state Water Quality standard for maximum temperatures in Class AA streams (not to exceed 16.3 °C).

Except Huckleberry Creek (average daily minimum 18.1°C), minimum water temperatures ranged from 11.7 - 15.7°C.

Those Type 4 harvested streams included in this study had an average size of 0.00053 cms (0.02 cfs), considerably smaller than the maximum size of 0.009 cms (0.3 cfs) in the Forest Practices regulations. (We noted a number of larger Type 4 streams with riparian leave areas during our site candidate search.) Since the downstream zone of temperature influence is shorter for smaller streams, because they have less capability to store heat energy for downstream transport, the potential for downstream temperature impacts is reduced. More Type 3 receiving streams will be too large to be affected by temperatures of these typically small Type 4 tributaries.

Average daily maximum air temperatures in the harvested areas were observed to be higher than those within the riparian areas. For instance, air temperatures at Jimmy Come Lately Creek increased 8.7°C between the harvested area and the riparian zone (27.6°C to 18.9°C). Abernathy Creek air temperatures increased 5°C (23.9 to 18.9°C), and a drop of 4.3°C was observed at upper Thorn Creek (24.3 to 20.2°C).

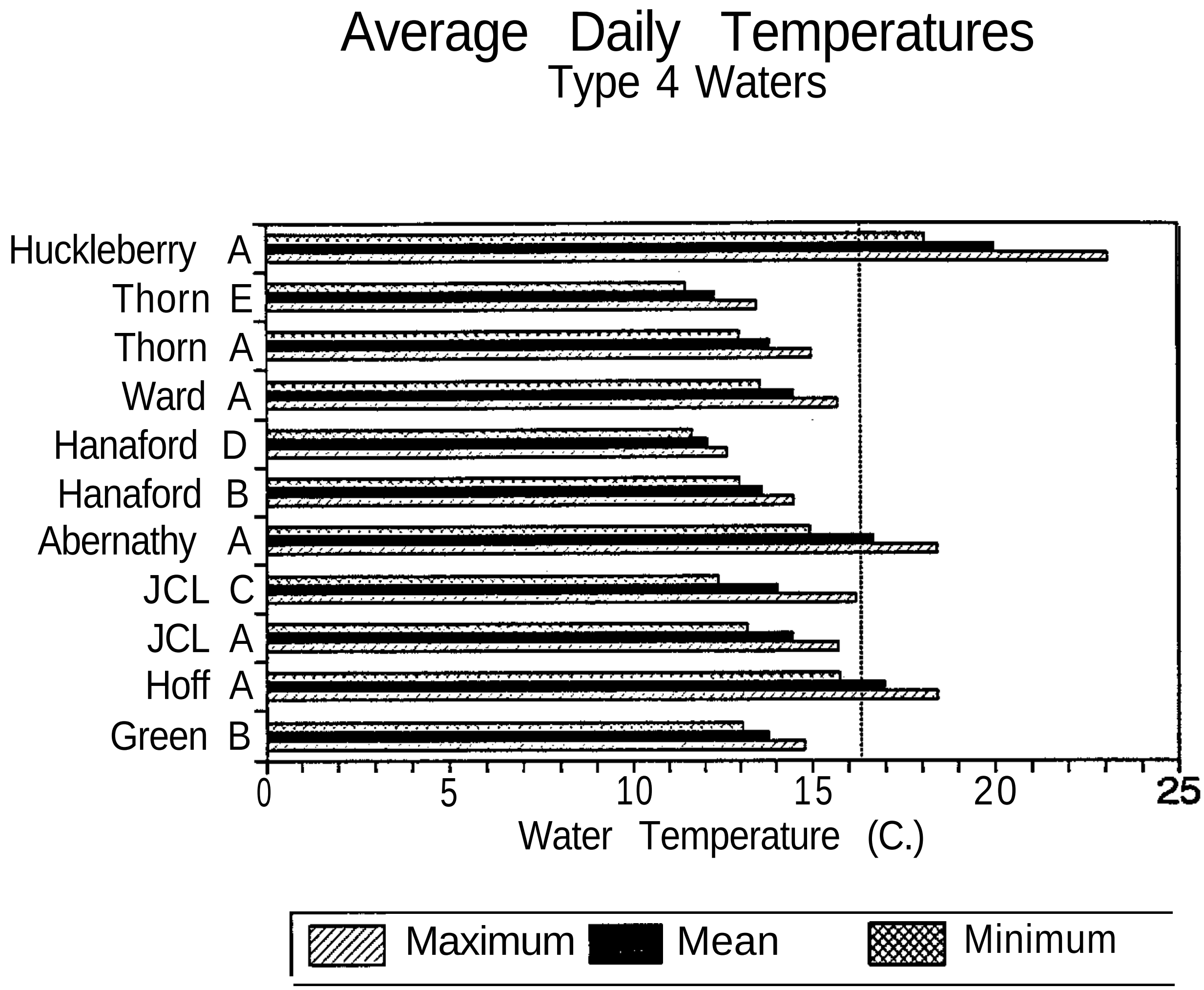


Figure 15. Average daily temperatures for harvested Type 4 study sites, summer 1990.

1990 Air Temperatures Compared to Lone-term NOAA Averaees

NOAA monthly climatological records were consulted for an indication of 1990 summer air temperatures in relation to long-term averages. Using the NOAA "division data" for Western Washington climate zones (temperature records grouped in areas with similar climatological characteristics), it appears that 1990 temperatures were slightly warmer than the long-term averages.

Table 2. 1990 Climate Information

NOAA climate division	Departure from "Normal" temperatures (degrees C, positive numbers indicate temperatures warmer than normal)		
	July	August	September
West Olympic/ Coastal	1.8	1.7	1.8
N.E. Olympic	1.5	1.5	0.9
Puget Lowlands	1.6	1.7	1.4
E. Olympic/ Cascade Foothills	2.0	1.7	1.9
Cascade Mtns. West	2.4	2.1	1.5

Overall Average: 1.7 degrees C warmer than "normal"

(NOAA 1990)

Temperature Screen Evaluation

One of the products on T/F/W research into stream temperature was a simple evaluation tool, for determining expected stream temperatures before and after timber harvest. This temueerature screen, presented in Sullivan and others (1990), is not used to predict actual stream temperatures, but rather to predict temperature categories, according to standards set by the Washington State Water Quality regulations (WAC 173-201). In this discussion, a "Low" temperature category refers to a stream with maximum temperatures less than 16.3°C (meeting the Water Quality criteria for class AA streams). A "Moderate" category refers to streams with maximum temperatures between 16.3 and 18.3°C (meeting the Water Quality criteria for class A streams). A "High" temperature category refers to streams with maximum temperatures exceeding 18.3°C (see Figure 16).

The temperature screen was developed using information from the Type 1-3 streams studied in 1988, and correctly predicted temperature categories of 89% of those streams. We wished to investigate the temperature screen's accuracy with this data set, to see if the smaller, shallower Type 3 and 4 streams we studied behaved in similar ways with respect to the screen as the previous data, which was from larger stream reaches.

We hypothesized that the general relationship of stream temperatures to shading level and site elevation expressed by the screen would hold true for these smaller streams as well, but that the exact stream temperatures might vary. On one hand, smaller streams will have a greater proportion of groundwater than larger streams, and might be expected to be cooler than a larger stream for a given shade level and site elevation. However, smaller streams are shallower, and could also be expected to be warmer for a given shade level and site elevation than a larger stream.

Methods

Homogeneous reaches within each study stream were defined, and the most downstream monitoring point in the homogenous reach was used to test the temperature screen. Reaches known not to be in temperature equilibrium with channel conditions were excluded.

The temperature screen requires an estimate of each site's shading level and elevation. Shading level at each site was specified by using the higher value from either the shade canopy measurements or from estimates of ground level shading from understory plants and logging debris. Site elevation was determined either from field altimeter measurements, or from USGS maps. Each site was plotted on the screen, and the temperature category predicted by the screen was compared to the actual temperature category, determined by the maximum recorded temperatures.

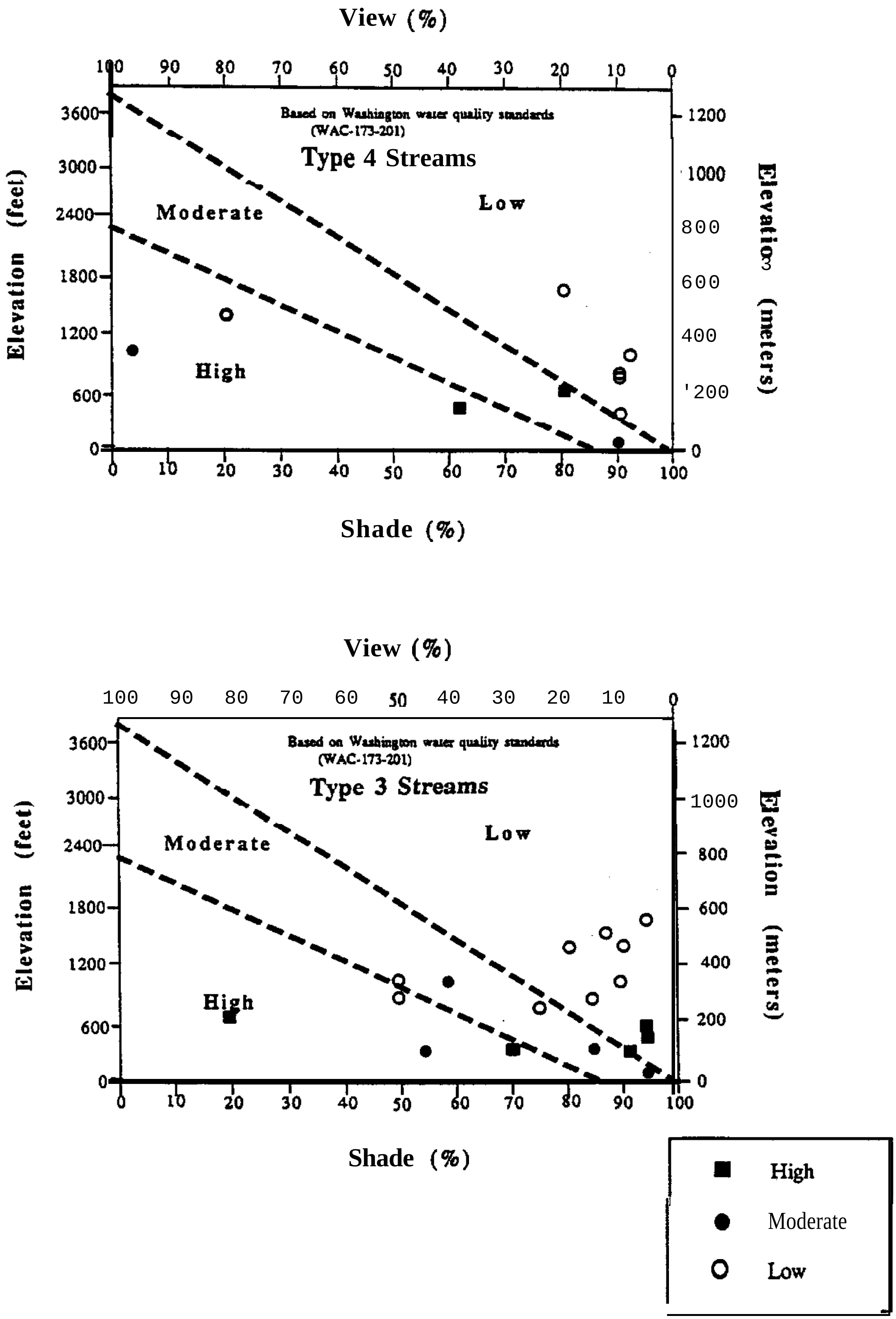


Fig. 16 Temperature Screen. Application of the temperature screen developed for Type I-3 waters (Sullivan and others, 1990) to the 1990 Type 4 study sites. The upper graph pbts the Type 4 streams while the bwer graph plots the small downstream Type 3 study sites.

Results

While the shade/elevation relationships presented in the screen did hold true, in general, local site conditions seemed to have a strong influence on temperatures of these small stream reaches. Some temperatures were much lower than the screen predicted, indicating an influence of groundwater. Some temperatures were higher, indicating an absence of groundwater, or simply atypically warm conditions.

A total of 28 reaches (18 Type 3 reaches and 10 Type 4) were tested against the screen. Seventeen reaches (60%) were correctly classed by the screen for temperature category. Eleven reaches (40%) were incorrectly classified (7 Type 3 reaches, and 4 Type 4 reaches). Six sites were classed too high, and 5 sites too low. Results are presented in Table 3 and Figure 16.

There was a relatively wide range of stream depths present in the 1988 dataset from which the screen was developed. Since the 1990 data included shallower streams, some inaccuracy in screen classifications might be expected. Small, shallow streams will be more strongly influenced by localized conditions so categorizing is less successful. Also, many of the sites were at low to moderate elevations making them susceptible to changes in temperature category with relatively minor changes in shade.

Table 3 . Temperature Screen Evaluation

Site/ Monitoring Point	Elevation (m)	% Shade Canopy	% Shade Brush	Maximum water Temp(C)	Actual Temperature category	Screen Temperature Category/ Screen Fit
Type 3 Streams						
Hanaford C	270	33	50	16.5	Low	High N
Hanaford E	270	85	10	15.0	LAW	Low Y
Hanaford G	244	75	40	14.5	Low	Low Y
Green A	109	70	0	17.8	High	Mod. N
Green E	109	85	25	17.1	Moderate	Mod. Y
Green F	109	55	15	17.4	Moderate	High N
Thorn B	580	95	10	14.5	Low	Low Y
Thorn c	530	87	10	13.5	Low	Low Y
Thorn D	480	90	50	12.0	Low	Law Y
Thorn F	480	80	20	13.0	Law	Law Y
Thorn H	363	46	50	12.5	Low	Mod. N
Huckleberry A	207	0	20	23.1	High	High Y
Abernathy F	195	95	10	18.5	High	Low N
JCL D	326	59	7	17.1	Moderate	Mod. Y
JCLE	326	90	35	16.2	Low	Low Y
Hoff C	146	95	26	18.8	High	Low N
Hoff E	91	98	17	19.6	High	Low N
Ward D	12	95	50	17.0	Moderate	Mod. Y
Tvpe 4 Streams						
Hanaford B	280	0	90	14.5	Low	Low Y
Hanaford D	270	0	90	15.0	Low	Low Y
Green B	109	5	90	15.7	Low	Low Y
Thorn A	580	0	80	15.0	Low	Low Y
Thorn E	480	0	20	13.5	Low	High N
Abernathy A	200	0	80	21.5	High	Mod. N
JCLA	326	93	3	16.7	Low	Mod. N
JCLC	326	-0	3	17.2	Moderate	High N
Hoff B	166	62	47	19.8	High	High Y
Ward A	12	0	90	18.0	Moderate	Mod. Y

Multiole Type 4 Tributaries

Thus far only the downstream temperature effects of a single Type 4 stream have been discussed. T/F/W managers have expressed concern about the potential for a cumulative downstream effect of multiple Type 4 streams on Type 3 receiving waters. Information gained on response distance allows this concern to be framed in a quantitative analysis. Since site data showed the effect on temperature from the Type 4 only extends 150 m or less downstream of the Type 4/3 boundary, only multiple Type 4 tributaries within a 150 m reach are of concern. Type 4 streams entering a Type 3 water at intervals greater than 150 m will have no cumulative effect.

To address the issue of a cumulative temperature impact the distribution of Type 4/3 stream boundaries was analyzed for western Washington forested lands. (A Type 4/3 stream boundary is defined as a place where a Type 4 reach either becomes a Type 3 reach, or is tributary to one.) Ten township maps were generated by the DNR Geographic Information System, with all streams shown. Since not all townships are available on the GIS, selection was not random, but townships were chosen to represent typical timberland areas in various counties in western Washington.

Table 4 describes the townships chosen. On each map, the total number of Type 4/3 stream boundaries were counted. The total number from all townships was 295, ranging from a low of 8 to a high of 58 in one township.

Three types of stream boundaries were seen. The first, single channel, was where a single stream changed class from a Type 4 to a Type 3 without gaining any tributaries. A total of 45%, or 134 boundaries, were of this type.

The second type, headwaters tributaries, was where two Type 4 streams joined, and the Type 3 boundary was at their confluence. A total of 12%, or 36 boundaries, were seen of this type. The maximum summer low flow at the confluence could not exceed 0.017 cms (0.6 cfs), and Type 3 streams of this size are included in this study. Stream temperatures would be expected to come into equilibrium with the Type 3 channel conditions in distances of 150 meters or less.

The third boundary type found was where the Type 3 stream gained Type 4 tributaries. A total of 42%, or 125 boundaries, were found in this sample. The mean distance between Type 4 tributaries in typical western Washington topography was 542 meters, with a range of 200 to 1013 meters. Since this distance, on average, is much longer than the 150 meters our study results indicate is the zone of concern, it would appear that there is little risk of cumulative temperature impacts of multiple Type 4 tributaries on Type 3 streams in western Washington.

A Type 4 stream may cause some localized effect on downstream water temperatures but the downstream waters will be in equilibrium to their own surrounding conditions, not the upstream Type 4 stream, within 150 m. In almost all cases this would be before a second Type 4 tributary enters, thus no cumulative effect exists.

For those rare instances where Type 4 tributaries enter a Type 3 water at intervals less than 150 m, a flow mixing equation, described in the methods section of this report could be used to identify if a potential for cumulative effect existed at that site's elevation, stream size and shade level.

Table 4. Distribution of Type 4/3 Stream Boundaries for Selected Areas in western Washington.

Township	County	No. of Type 4/3 stream boundaries			Average downstream distance (m) between Type 4/3 stream boundaries
		Single channel	Headwater tributaries	Multiple tributaries	
T27N R8E	Snohomish	15	0	3	363
T6N R4E	Cowlitz	11	1	4	539
T15N R8W	Lewis	13	8	39	241
T16N R4W	Pacific	29	6	14	498
T16N R7W	Thurston	5	3	5	1013
T31N R12W	Grays Harbor	21	11	26	619
T34N R7E	Clallam	17	3	5	968
T39N R7E	Skagit	10	3	25	385
T39N R4E	Whatcom	6	1	3	591
T28N R1E	Jefferson	7	0	1	202

VI Discussion and Conclusions

Characteristics of Tvoe 4 waters

The analysis using the temperature screen, as well as the site by site descriptions in section V, indicate that the Type 4 reaches studied act, with regard to temperature, much like the larger streams studied in the 1988-1990 T/F/W temperature study. Reductions in shade levels result in an increase in stream temperature. Harvested Type 4 streams may be 2 - 8°C higher than would be expected for similar streams under a mature riparian canopy. The temperature of Type 4 streams is strongly influenced by elevation in the same manner as other streams (Sullivan and others, 1990). Low elevation streams are warmer, with temperatures recorded up to 21.5°C at very low elevations for open canopy streams. Stream temperatures for moderate elevation streams observed in this study were well below the regulatory limit of 16.3°C for Class AA streams in Washington.

Since Type 4 streams are small by regulatory definition their temperature response to changes in channel conditions is rapid, and conditions within the immediate stream reach control the temperature within these streams. Localized conditions affecting temperature include: air temperature, elevation, groundwater inflow, and shade.

This study showed that Type 4 streams are influenced by air temperatures. However a maximum equilibrium temperature exists for streams above which water temperatures will not increase, even if air temperatures do. This maximum equilibrium temperature is dictated by channel conditions, particularly elevation and shade, and is partially independent of air temperature. Elevation affects both air temperatures and the efficiency of heat energy exchange processes (Edinger and others, 1968). The close fit of the Type 4 stream data to the temperature screen supports the importance of the effect of elevation on temperature.

Groundwater strongly influences temperatures in small Type 4 streams. Groundwater inflow which enters the stream at cool temperatures (10 - 12.5°C average) is proportionately large with respect to the total flow in headwater streams. Groundwater rates appear to vary widely geographically. Where groundwater inflow rates are substantial, the Type 4 stream temperature is largely a function of groundwater temperature. Type 4 streams are responsive to very localized groundwater conditions as well as to the other localized conditions affecting stream temperature. The daily temperature profiles (Appendix B) for Thorn Creek graphically demonstrate the strong influence of groundwater. As a comparison, the daily temperature profiles for Hoff Creek, where groundwater recharge was documented, closely track air temperature with little effect of groundwater temperatures.

High temperatures in harvested Type 4 streams were not as common as some had expected. Temperatures in harvested Type 4 streams are as much as 2-8°C higher than for streams at similar elevations with mature forest canopies. However, many of the harvested Type 4 streams displayed cool water temperatures well below the water quality standards. One of the reasons for this is that, in most cases, substantial amounts of understory shade remain after harvest of the trees. Brush and slash remaining after harvest accounted for an average of 40% shade for the study sites. During site selection numerous sites were not chosen because a dense understory canopy had developed on stream channels where harvest had occurred four or more years previously.

A last point is that shade reduction in a completely harvested Type 4 reach is a relatively short-lived phenomena, existing for less than 5 years in stream reaches not affected by catastrophic flooding events. Even within that five-year period, many sites contain a fair level of channel shading from understory plants and wood debris. Both this shading, and in some cases the relatively high proportion of groundwater flow, can tend to depress stream temperatures even though air temperatures in the harvested units are typically higher than those in nearby riparian areas.

The sample size of streams studied for this project is too small to specifically characterize Type 4 streams separately from adjoining Type 3 reaches, or to make any generalizations regarding streams across Washington state (our sample did not include sites in Eastern Washington). However, there is no indication that the small Type 4 and 5 streams react in any way differently than the Type l-3 streams studied in the 1988-1990.

Of the 11 Type 4 stream reaches with distinctive channel characteristics (includes Huckleberry Creek which is a regulated as a small Type 3) eight met the Class AA maximum temperature water quality standard, i.e. less than 16.3°C. Those sites which did not meet the water quality standard were at lower elevations; approximately 200 m or less. The warmest creek, Huckleberry, had experienced a dam break flood which scoured the channel and most of the brush shading the channel. The five reaches with maximum temperatures exceeding 16.3°C also had warmer minimum temperatures relative to other sites. The effect of elevation on temperature does not fully account for these warmer minimum temperatures. Summer minimum temperatures in small streams are typically at or near groundwater temperature. The higher minimum temperatures suggests groundwater inflow was minimal within these five reaches.

Downstream effects of Tvoe 4 waters on Tvoe 3 waters

Increases to stream temperature for salmonid bearing (i.e., downstream) waters resulting from timber harvest on upstream Type 4 waters appear to be negligible. In cases where a single stream channel changed from a Type 4 to Type 3 water type, short response distances were seen, in response to changes in the riparian shading levels. Maximum equilibrium temperatures were quickly established dependent on the downstream conditions once the water entered the Type 3 (shaded) reach. The response distance was typically 150 meters or less with no effect on temperature from the harvested Type 4 stream downstream of the response distance. Using measured stream velocities, these response distances equate to a water travel time on the order of one to two hours for equilibrium temperatures to be reached. This conforms with the analysis of equilibrium response time presented in Adams and Sullivan (1990).

With regard to Type 4 streams flowing into an independent Type 3 stream, the flow mixing equation which is a weighted average of the incoming stream temperatures (Brown, 1969), fully describes the temperature response. The response of the Type 3 stream never exceeded 0.5°C change in temperature attriiutable to the incoming Type 4 stream. Reasons include the typically small size of the Type 4 mbutaries in relation to the Type 3 receiving streams, and the relatively cool temperatures seen in some Type 4 reaches despite total removal of overstory canopy. This lack of response was seen both in cases where warm and where cool Type 4 streams flowed into Type 3 reaches.

The flow mixing equation can also be used to demonstrate minimal downstream effect from Type 4 streams. Assuming a warm Type 4 stream (21.5°C, the highest temperature observed) with a low flow of 0.009 cms flowing into a cool Type 3 stream (for example, 15.8°C), the size of the downstream Type 3 stream which would be affected can be calculated using the mixing equation. This calculation shows that, in this worst case situation, the Type 3 must be no larger than 0.09 cms to be affected. If the Type 3 were any larger relative to the Type 4, the effect on temperature would not be great enough to result in the Type 3 exceeding the water quality standard for class AA streams (the temperature would remain below 16.3°C.) Sullivan and others (1990) related minimum stream flow to distance from watershed divide. Using this relationship and the results of the flow mixing equation, it can be concluded that the temperature in Type 3 streams greater than seven km (4.5 miles) distance from watershed divide (measured along the Type 3 stream channel) would not be affected by incoming Type 4 waters. This holds true for incoming Type 4 streams which are both cooler and warmer than the receiving Type 3 stream. This distance from divide was calculated using a worst case scenario for the Type 4 temperatures. Effects of Type 4 mbutaries on downstream Type 3 water temperatures are commonly more limited.

$$\frac{(21.5°C * 0.009\ cms) + (15.8°C * Q_3)}{0.009\ cms + Q_3}$$

Where Q_3 = stream discharge in the Type 3 receiving water

Riparian management along Type 4 streams for temperature control will only affect water temperatures within the Type 4 and for a limited downstream distance in Type 3 waters. Type 3 streams beyond 7 km from watershed divide will have virtually no effect with respect to temperature impacts from incoming Type 4 streams. Though there may be downstream effects other than temperature, in most cases harvest within Type 4 streams does not seem to affect stream temperatures for salmonid bearing waters.

Multiple Type 4 Triiutaries

T/F/W managers have expressed concern as to the cumulative downstream effect of multiple Type 4 streams. Since site data showed that the effect on temperature from a Type 4 stream only extends 150 m or less downstream of the Type 3/4 interface, only multiple Type 4 tributaries within 150 m are of concern. Type 4 streams entering a Type 3 at greater space intervals will have no cumulative effect. A map analysis for western Washington forested lands indicated that Type 4 tributaries to a Type 3 stream are typically spaced at 200 m to greater than 1000 m intervals; thus no cumulative temperature impact could occur. In the case of one or two headwater Type 4 streams converting to a downstream Type 3 stream any elevated temperatures due to harvest along the Type 4 would only persist 150 m downstream. Type 4 streams flowing into Type 1 and Type 2 waters would have no discernable effects on water temperature.

Stream Depth and Temperature Response

Stream depth is one of the most important channel characteristics which control a stream's rate of temperature response. Heat energy transfer processes are more rapid in shallower streams and thus shallow streams can potentially have greater diurnal temperature fluctuations in response to diurnal climate patterns. Shallow streams respond rapidly to direct solar radiation reaching the stream's surface (Brown, 1969). Shallow streams are apt to respond to changing channel conditions as the water passes downstream within l-2 hours or less whereas large rivers may only respond within several days or more to changing ambient conditions (Adams and Sullivan, 1990).

Average stream depths of streams studied in 1988 (Types 1-3 reaches) can be compared to average depths of the smaller Type 3 and 4 stream reaches studied for this project. Both sets of data, considered together, present a range of typical stream depths for each various water type. Stream depths in the 1988 study ranged from 0.13 - 0.56 m for Type l-3 waters while Type 3 and 4 streams included in this study ranged from 0.07 - 0.56 m in depth. The 1990 data include the lower end of the range present in Washington streams.

The response distance of 150 m or less is comparable to a response time of 1 - 2 hours given the velocities of the streams studied. This fairly rapid response is due to the shallow nature of these streams. Deeper Type 1 - 3 streams can be expected to respond slower to changing ambient conditions and thus have somewhat longer response distances.

VII Recommendations

Increases to stream temperature for salmonid bearing (i.e., downstream) waters resulting from timber harvest on upstream Type 4 waters appear to be negligible. Maximum equilibrium temperatures were quickly established dependent on the downstream conditions once the water entered the Type 3 (shaded) reach. The response distance was typically 150 meters or less with no effect on temperature from the harvested Type 4 stream downstream of the response distance.

We recommend that management recommendations to T/F/W be developed following a technical review of this report. Management recommendations should recognize the limited downstream temperature effect of harvest along Type 4 waters. Furthermore, cumulative effects from multiple Type 4 waters entering Type 3 or larger waters seldom occur for western Washington streams. The potential for cumulative temperature impacts for Type 4 streams in eastern Washington could be similarly examined using maps for that region.

A policy decision is required regarding management actions to regulate stream temperature within Type 4 stream reaches as opposed to downstream effects. Several of the Type 4 streams monitored in this study exceeded the Washington water quality standards (WAC 173-201). However, temperatures exceeding of the water quality standard were seen for both harvested and forested Type 4 streams. This study was not geographically comprehensive and the number of streams is too small to fully characterize the range of temperature regimes within Washington's Type 4 waters. If shade recommendations are developed for controlling stream temperatures within Type 4 streams themselves, it is recommended that additional sites be investigated to characterize Type 4 water temperature regimes. Maximum - minimum thermometers placed in streams at various elevations, ecoregions, and shade levels for a few days during July 15 - August 15 would suffice for characterizing maximum temperatures. The maximum equilibrium stream temperature will be observable using this simple approach. Any management regulations adopted for control of stream temperature within Type 4 waters should recognize the effect of elevation as well as shade on stream temperature. Unlike larger Type l-3 streams, use of the temperature screen to categorize stream temperatures is not recommended for Type 4 streams. The strong influence of localized conditions, particularly groundwater inflow rate and temperature, render the screen less applicable to Type 4 waters.

The conclusions and recommendations for the management of riparian areas along Type 4 streams are only based on stream temperature concerns. Numerous other factors also must be considered in the management of forest practices along type 4 streams. Though downstream temperature impacts are negligible, erosion and other factors are still relevant to the management of Type 4 streams.

References

Adams, T.A. and K. Sullivan, 1990. The physics of forest stream heating: a simple model. Timber/Fish/Wildlife Report TFW-WQ3-90-007, Washington Dept. of Natural Resources, Olympia, WA.

Beschta, R.L. and W.S. Platts, 1986. Morphological features of small streams: significance and function. Wat.Res.Bull. 22(3):369 - 379.

Brown, G.W., 1969. Predicting temperatures of small streams. Wat. Resources Res. S(1): 68 - 75.

Doughty, K., J.E. Caldwell and K. Sullivan, 1990. Work plan: evaluation of downstream temperature effects of riparian management on Type 4 waters, submitted to Cooperative Monitoring and Research Committee, Timber/Fish/Wildlife, June 1990.

Dunne, T. and L.B. Leopold, 1978. Water in environmental planning. W.H. Freeman and Co., San Francisco, CA.

Edinger, J.E. and J.C. Geyer, 1968. Analyzing stream electric power plant discharges. J.Sanit.Eng., Proc. Amer. Soc. Civil Eng., 94(SA4): 611-623.

Hynes, H.B.N, 1970. The ecology of running waters. University of Toronto Press, Toronto, Canada. 55.5 pp.

MacDonald, A., and K.W. Ritland, 1989. Sediment dynamics in Type 4 and 5 waters: a review and synthesis. T/F/W Report TFW-012-89-002, Washington Dept. of Natural Resources, Olympia, WA.

National Oceanographic and Atmospheric Administration, 1990. Local Climatological Data, Monthly Summary (Yakima Airport, Olympia Airport, Seattle/Tacoma Airport), National Climatic Data Center, Asheville, N.C.

National Oceanographic and Atmospheric Administration, 1990. Climatological Data, Washington, July-September, 1990, National Climatic Data Center, Asheville, N.C.

Sullivan, K., S.H. Duncan, P.A. Bisson, J.T. Heffner, J.W. Ward, R.E. Bilby, and J.L. Neilson, 1987. A summary report of the Deschutes basin: sediment, flow, temperature and fish habitat. Weyerhaeuser Co. Technical Report, Paper # 044-.5002/87/1, Tacoma, WA.

Sullivan, K., J. Tooley, K. Doughty, J.E. Caldwell and P. Knudsen, 1990. Evaluation of prediction models and characterization of stream temperature regimes in Washington. Timber/Fish/Wildlife Report TFW-WQ3-90-006, Washington Dept. of Natural Resources, Olympia, WA.

Summers, R., 1982. Trends in riparian vegetation regrowth following timber harvesting in western Oregon watersheds. M.S. thesis. Oregon State University, Corvallis, OR.

Tennessee Valley Authority, 1972. Heat and mass transfer between a water surface and the atmosphere. Water Res. Lab. Report # 14, Norris, TN.

Theurer, F.D., K.A. Voos and W.J. Miller, 1984. Instream water temperature model, Instream Flow Information Paper # 16. U.S. Fish & Wildlife Service FWS/OBS-84/15.

Washington Administrative Code, Chapter 173-201. Water Quality Standards for Surface Waters of the State of Washington.

Washington State Forest Practices Board, 1988. Washington Forest Practices Rules and Regulations. Washington Dept. of Natural Resources, Olympia, WA.

Appendix A Site Characteristics

Site Name: Abernathy Creek

Tributary to: **Columbia River** **WRIA: 25**

Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**	**F**
T/S/R	**S9,T9N,R4W**						
Latitude	46-10						
Longitude	123-00						
Instrument type	**Datapod,** Unidata						
Start date	**8/4/90**						
End date	**8/28/90**						
Site visit	**8/28/90**						
Cumulative downstream distance (m)		**0**	**0**	**0**	**5**	**26**	**39**
Maximum water temperature observed		21.5	18.5	20.8	18.6	19	18.5
Elevation (m)		200	195	195	195	195	195
Average width (m)		1.39	6.26	1.39	6.26	6.26	6.26
Average depth (m)		**0.09**	**0.52**	**0.09**	**0.52**	**0.52**	**0.52**
Discharge **(cms)**		0.0085	0.1470	0.0140	0.1470	0.1470	0.1470
Velocity (m/s)		0.01	0.22	0.06	0.22	0.22	0.22
Stream azimuth		**80E**	140E	**80E**	140E	140E	140E
Canopy Cover (% shade)		**0**	**96**	**96**	**96**	**95**	**95**
Brush Cover **(%** shade)		80	10	10	10	10	10
Canopy Characteristics Type 4	Brush						
Canopy Characteristics Type 3	Mature alder/conifer RMZ						
Substrate	Sm **boulder/lg** cobble/gravel						
Sideslope Gradient **(%)**		**RB&LB**	**<** 10	30-40	**<** 10	**<** 10	**<** 10

Appendix A Site Characteristics

Site Name	Green Cr.						
Tributary to	**Pysht River WRIA : 19**						
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**	**F**
T/S/R	**S22,T31N,R12W**						
Latitude	48-10						
Longitude	124-25						
Instrument type	Ryan						
Start date	**8/16/90**						
End date	**9/11/90**						
Site visit	**9/11/90**						
Cumulative downstream distance (m)		**0**	**0**	**159**	**313**	**427**	**610**
Maximum water temoerature observed		17.8	15.7	17.3	17	17.1	17.4
Elevation (m)		109	109	109	109	109	109
Average width (m)		2.20	1.04	1.80	2.37	1.27	2.72
Average depth (m)		**0.17**	**0.09**	**0.12**	**0.25**	**0.25**	**0.16**
Discharge (cms)		**0.0079**	**0.0018**	**0.0079**	**0.0079**	**0.0051**	**0.0051**
Velocity (m/s)			0.03	0.08			
'Stream azimuth							
Canopy Cover (% shade)		**70**	**5**	**85**	**85**	**85**	**55**
Brush Cover (% shade)		**0**	**90**	**30**	**0**	25	15
Canopy Characteristics Type 4	Brush						
Canopy Characteristics Type 3	Alder RMZ						
Substrate	Cobble & gravel						
Sideslope Gradient (%)		0	15	15	15	10	0

Appendix A Site Characteristics

Site Name		Hanaford Creek						
Tributary to	4	Skookumchuck R.		WRIA: 23				
Monitoring Point	ALL	A	B	D	C	E	F	G
T/S/R	S3,T14N,R1E							
Latitude	46-40							
Longitude	122-40							
Instrument type	Datapod							
Start date	8\9\90							
End date	9\6\90							
Site visit	8\9\90							
Cumulative downstream distance (m)		0	0	140	0	152	305	609
Maximum water temperature observed		14.5	14.5	16.5	15	15	15	14.5
Elevation (m)		280	280	270	270	270	260	244
Average width (m)		1.86	0.46	1.86	0.46	2.29	2.13	3.05
Average depth (m)		0.21	0.09	0.21	0.09	0.20	0.14	0.15
Discharge (cms)		0.0181	0.0025	0.0181	0.0028	0.0275	0.0275	0.0258
Velocity (m/s)		0.24	0.09	assume A	assume B	assume F	0.09	assume E
Stream azimuth		320W	260W	260W	320W	320W	340W	240W
Canopy Cover (% shade)		33	0	0	33	85	70	75
Brush Cover (% shade)		50	90	90	50	10	25	40
Canopy Characteristics Type 4	harvested/ logging debris							
Canopy Characteristics Type 3	Alder RMZ, devils club, vine maple							
Substrate		sm&l gra	sm gravel	sm gravel	sm&l gra	sm cobble	sm%lg	cobbles,ripra
Sideslope Gradient (%)		RB&LB	RB&LB	RB&LB	RB&LB	RB>60,LB>40		

Appendix A Site Characteristics

Site Name	Hoff Creek					
Tributary to	Nooksack River WRIA : 01					
Monitoring Point	ALL	A	B	C	D	E
T/S/R	S22,T39N,R4E					
Latitude	48-50					
Longitude	122-20					
Instrument type	Ryan					
Start date	7/30/90					
End date	8/14/90					
Site visit	8/14/90					
Cumulative downstream distance (m)		0	38	197	366	644
Maximum water temperature observed		19.8	19.8	18.8	19.4	19.6
Elevation (m)		166	164	146	140	91
Average width (m)		1.10	1.10	1.33	1.06	0.90
Average depth (m)		0.07	0.07	0.14	0.08	0.07
Discharge (cms)		0.0014	0.0020			0.0014
Velocity (m/s)		0.04		0.03		
Stream azimuth						
Canopy Cover (% shade)		51	62	95	98	98
Brush Cover (% shade)		32	47	26	17	17
Canopy Characteristics Type 4	Brush (also steep side slopes)					
Canopy Characteristics Type 3	Mature alder/conifer					
Substrate		cobble	cobble	boulder	gravel	gravel
Sideslope Gradient (%)		50	50	15	5	5

Appendix A Site Characteristics

Site Name		Huckleberry Creek			
Tributary to		**Deschutes R.**		**WRIA: 13**	
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**
T/S/R	**S17,R4E,T15N**				
Latitude	46-40				
Longitude	122-30				
Instrument type	**Unidata/Datapod**				
Start date	7127190				
End date	8127190				
Site visit	**8/27/90**				
Cumulative downstream distance (m)		**0**	**259**	**316**	**446**
Maximum water temperature observed		**23.1**	**19**	**20.5**	**19**
Elevation (m)		**207**	**207**	**205**	**200**
Average width (m)		**2.74**	**1.74**	**3.22**	**3.22**
Average depth (m)		**0.10**	**0.20**	**0.37**	**0.37**
Discharge (cms)		**0.0159**	**0.0159**	**0.0125**	**0.0125**
Velocity (m/s)		0.13		0.042	0.042
Stream azimuth		260w	**250W**	**280w**	320w
Canopy Cover (% shade)		**0**	**0**	**90**	**95**
Brush Cover (% shade)		20	100	2 0	20
Canopy Characteristics Type 4	Open, wide, small amt. log debris				
Canopy Characteristics Type 3	Lower end of logjam @ B, C & D mature alder				
Substrate		Small gravels		Gravel, sm & lg cob	
Sideslope Gradient (%)		All sites < 10			

Appendix A Site Characteristics

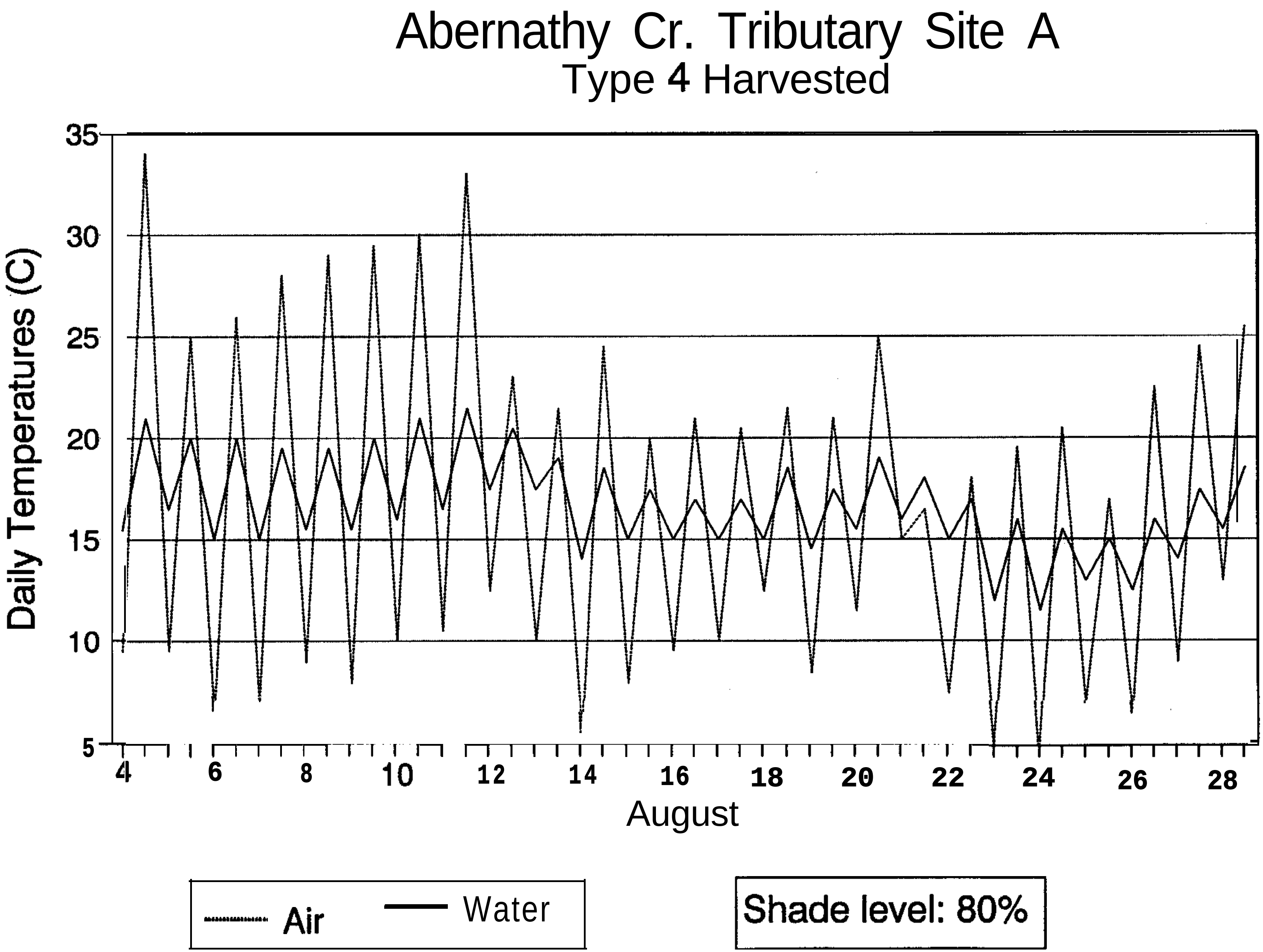
Site Name		**Jimmy Come Lately Cr.**				
Tributary to		**Sequim Bay WRIA : 17**				
Monitoring Point	**ALL**	**A**	**B**	**C**	**D**	**E**
T/S/R	**S22,T29N,R3W**					
Latitude	**48-0**					
Longitude	**123-0**					
Instrument type	**Ryan**					
Start date	**8/25/90**					
End date	**9/10/90**					
Site visit	**9/10/90**					
Cumulative downstream distance (m)		**0**	**152**	**305**	**457**	**610**
Maximum water temperature observed		**16.7**	**16.8**	**17.2**	**17.1**	**16.2**
Elevation (m)		**326**	**326**	**326**	**326**	**326**
Average width (m)		**1.10**	**1.09**	**1.17**	**1.14**	**1.52**
Average depth (m)		**0.09**	**0.14**	**0.10**	**0.08**	**0.18**
Discharge (cms)		**0.0054**	**0.0054**			**0.0065**
Velocity (m/s)			**0.10**			**0.04**
Stream azimuth						
Canopy Cover (% shade)		**93**	**11**	**0**	**59**	**90**
Brush Cover (% shade)		3	6	3	7	35
Canopy Characteristics Type 4		Mature deciduous above road; none for points B - C				
Canopy Characteristics Type 3		Selectively thinned conifer				
Substrate		gravel	gravel	gravel	gravel	gravel
Sideslope Gradient (%)		0	steep short banks (1		minimal	minimal

Appendix A Site Characteristics

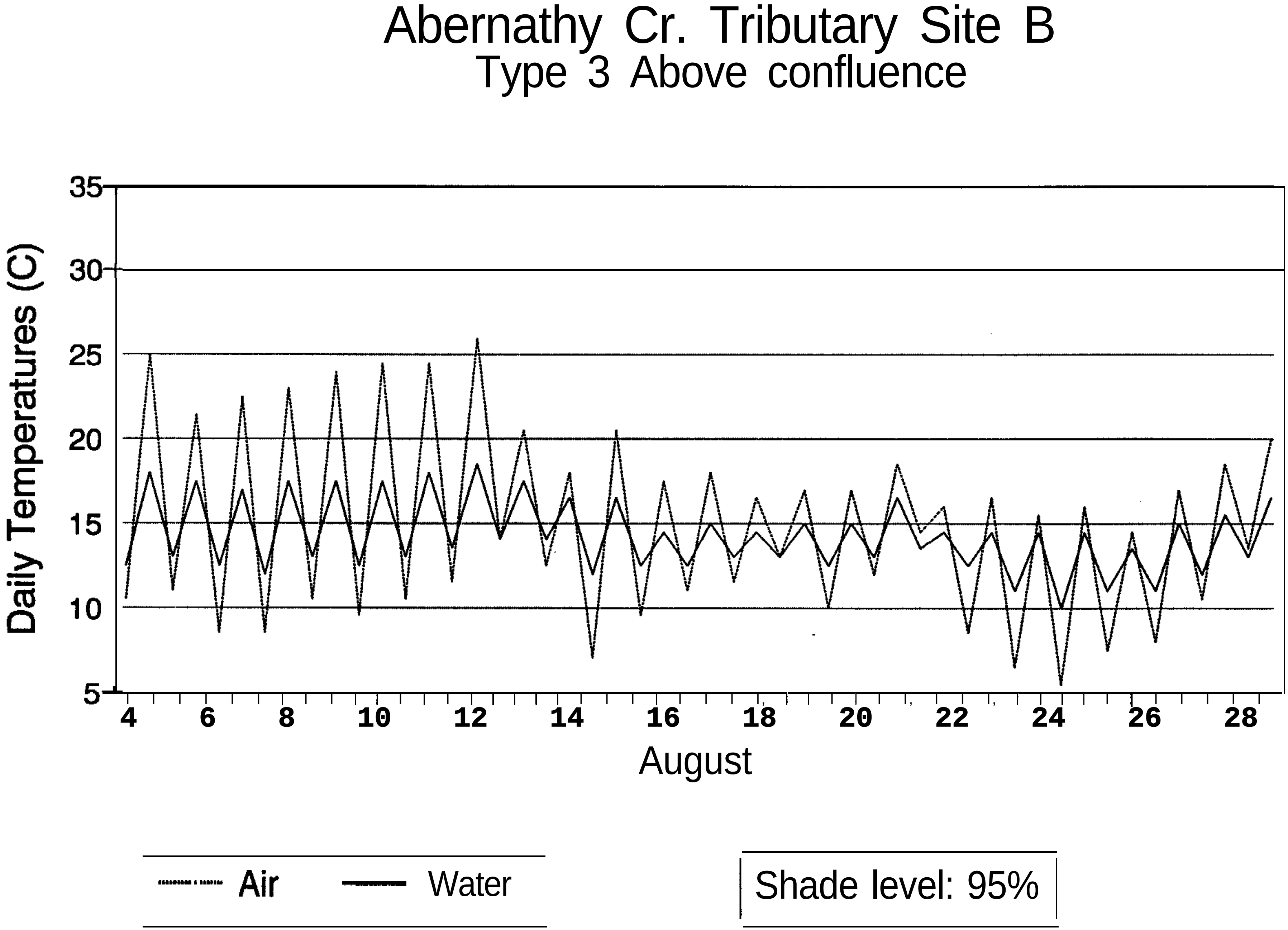
Site Name		Thorn Creek							
Tributary to		West Fork Cr. Deschutes River WRIA : 13							
Monitoring Point	ALL	A	B	C	D	E	F	G	H
T/S/R	**S11,T14N,R4E**								
Latitude	**46-40**								
Longitude	122-20								
Instrument type	**Datapod**								
Start date	**7/18/90**								
End date	**8/15/90**								
Site visit	**8/6/90**								
Cumulative downstream distance (m)	0	0	69	284	626	0	675	1268	1597
Maximum water temperature observed		1s	14.5	13.5	12	13.5	13	12.5	12.5
Elevation (m)		580	580	530	480	480	480	366	363
Average width (m)	**0.00**	**1.87**	**1.17**	**1.11**	**2.12**	**0.73**	**2.81**	**1.52**	**2.35**
Average depth (m)	0.00	0.12	0.09	0.21	0.18	0.11	0.35	0.28	0.28
Discharge **(cms)**		**0.0020**	**0.0020**	**0.0020**	**0.0020**	**0.0002**	**0.0031**	**0.0119**	**0.0202**
Velocity (m/s)		0.036	0.036		0.076	0.031	0.003	0.246	0.246
Stream azimuth		140E	160E	**100E**	**80E**	40E	40E	**45E**	40E
Canopy Cover (% shade)		0	95	87	90	0	80	25	46
Brush Cover **(%** shade)		80			**50**	20	20	60	**50**
Canopy Characteristics Type 4		Brush, grasses				Brush, grasses			
Canopy Characteristics Type 3		Alder RMZ, brush, **instream** logs							
Substrate	ble	Boulder/cobble							
Sideslope Gradient **(%)**		For all sites, **>** 60							

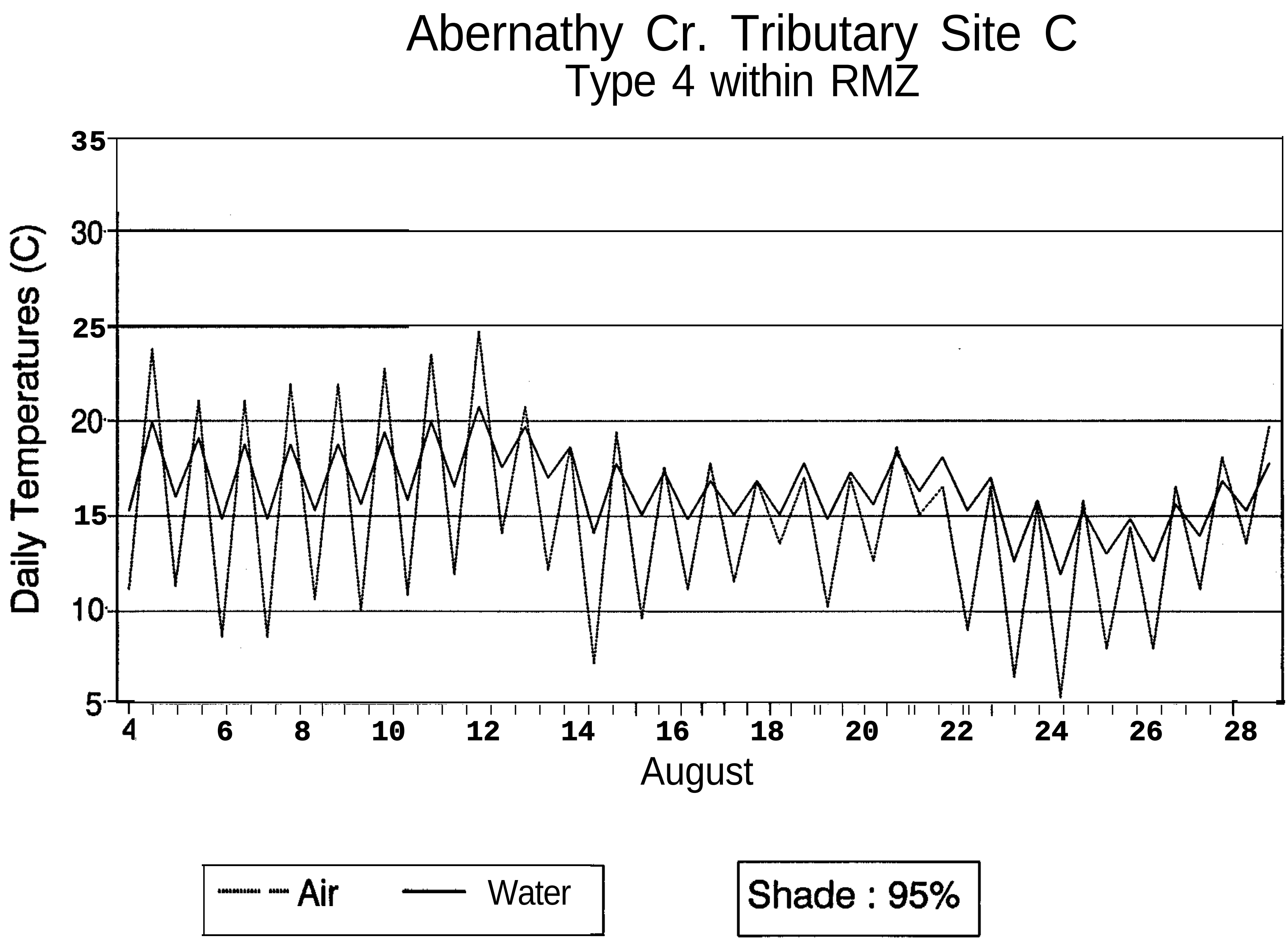
Appendix A Site Characteristics

Site Name		Ward Cr Tributary			
Tributary to		**Ward Creek, Willapa River**			**WRIA: 2**
Monitoring Point	**All**	**A**	**B**	**C**	**D**
T/S/R	**S14,T14N,R8W**				
Latitude	**46-40**				
Longitude	123-50				
Instrument type	**Datapod**				
Start date	**8/9/90**				
End date	**8/28/90**				
Site visit	**8/28/90**				
Cumulative downstream distance (m)		**0**	**26**	**153**	**249**
Maximum water temperature observed		**18**	**17.5**	**17**	**17**
Elevation (m)		**12**	**12**	**12**	**12**
Average width (m)		**0.46**	**0.76**	**0.76**	**0.76**
Average depth (m)		**0.09**	**0.09**	**0.09**	**0.09**
Discharge (cms)		**0.0050**	**0.0050**	**0.0050**	**0.0050**
Velocity (m/s)	**very low, estimated at 0.003 - 0.007 cms**				
Stream azimuth		**280W**	**300W**	**260W**	**200W**
Canopy Cover (% shade)		**0**	**95**	**95**	**96**
Brush Cover (% shade)		**90**	**50**	**50**	**50**
Canopy Characteristics Type 4	Brush only				
Canopy Characteristics Type 3	mature alder				
Substrate	**sand/small** gravels				
Sideslope Gradient (%)		30	0	0	0



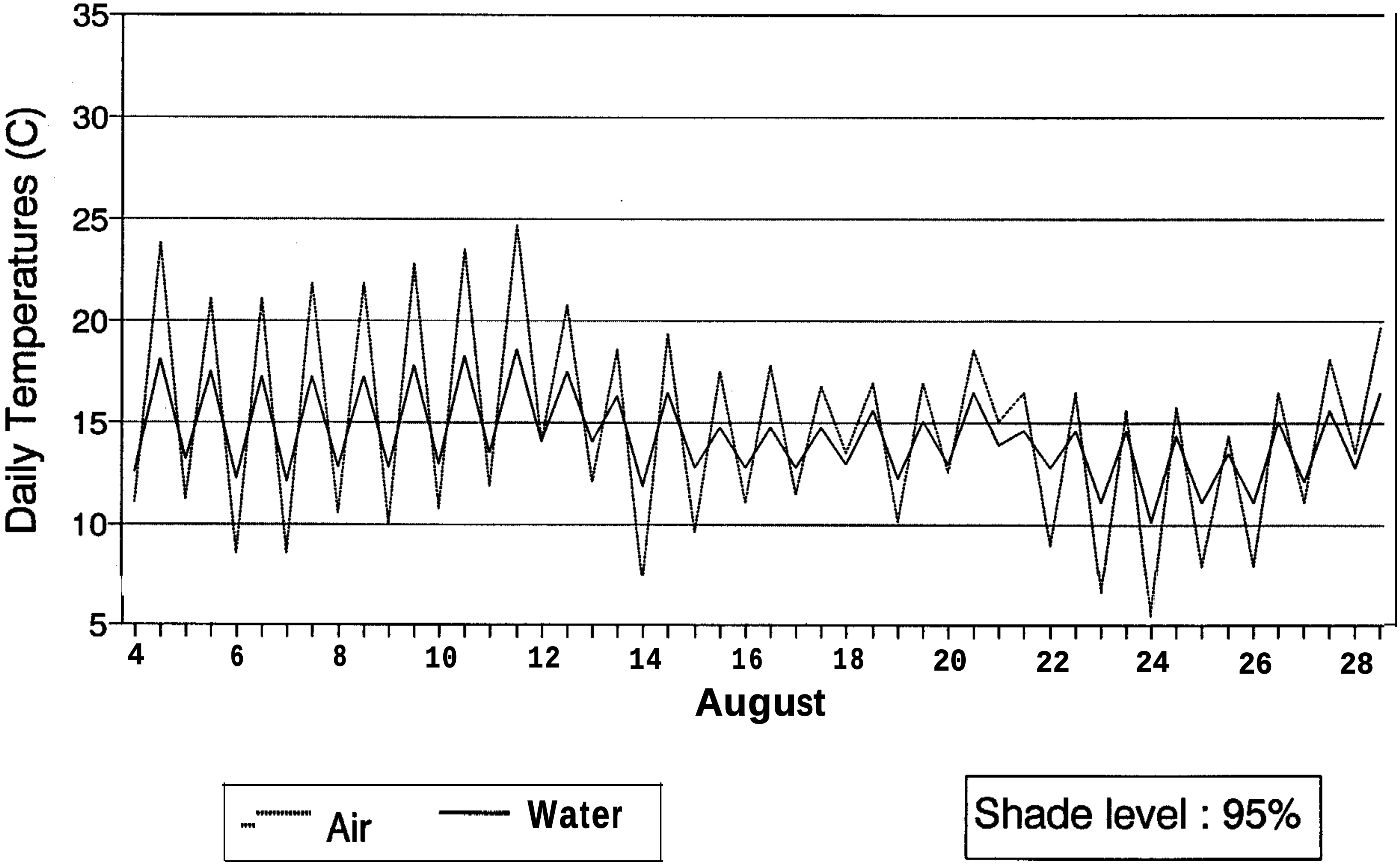
Abernathy Cr. Tributary Site A
Type 4 Harvested
Daily Temperatures (C)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24
26
28
August
Air
Water
Shade level: 80%


Abernathy Cr. Tributary Site B
Type 3 Above confluence
Daily Temperatures (C)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24
26
28
August
Air
Water
Shade level: 95%



Abernathy Cr. Tributary Site C
Type 4 within RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
4
6
8
10
12
14
16
18
20
22
24
26
28
August
Air
Water
Shade : 95%

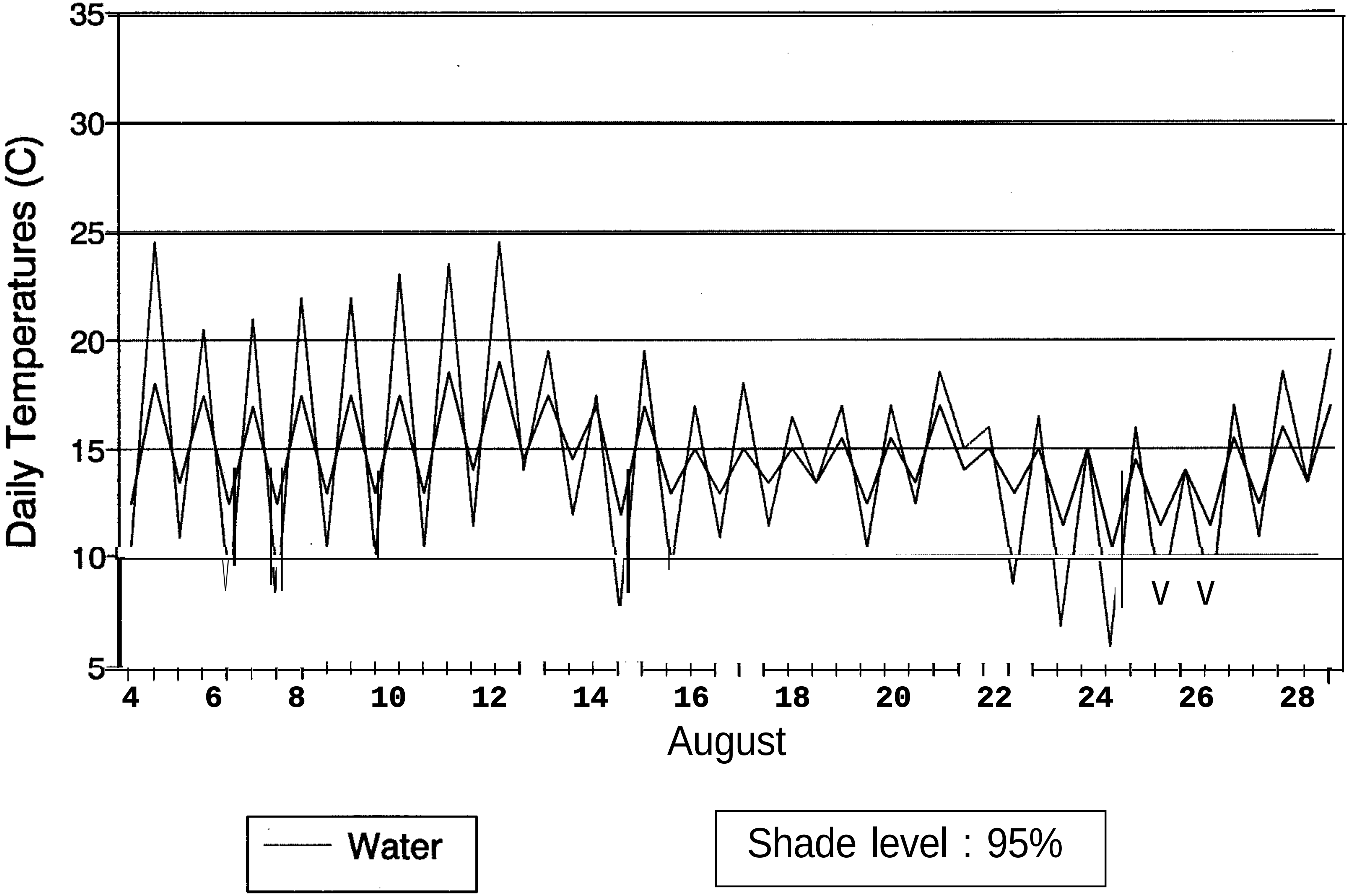
Abernathy Cr. Tributary Site D
Type 3 below confluence



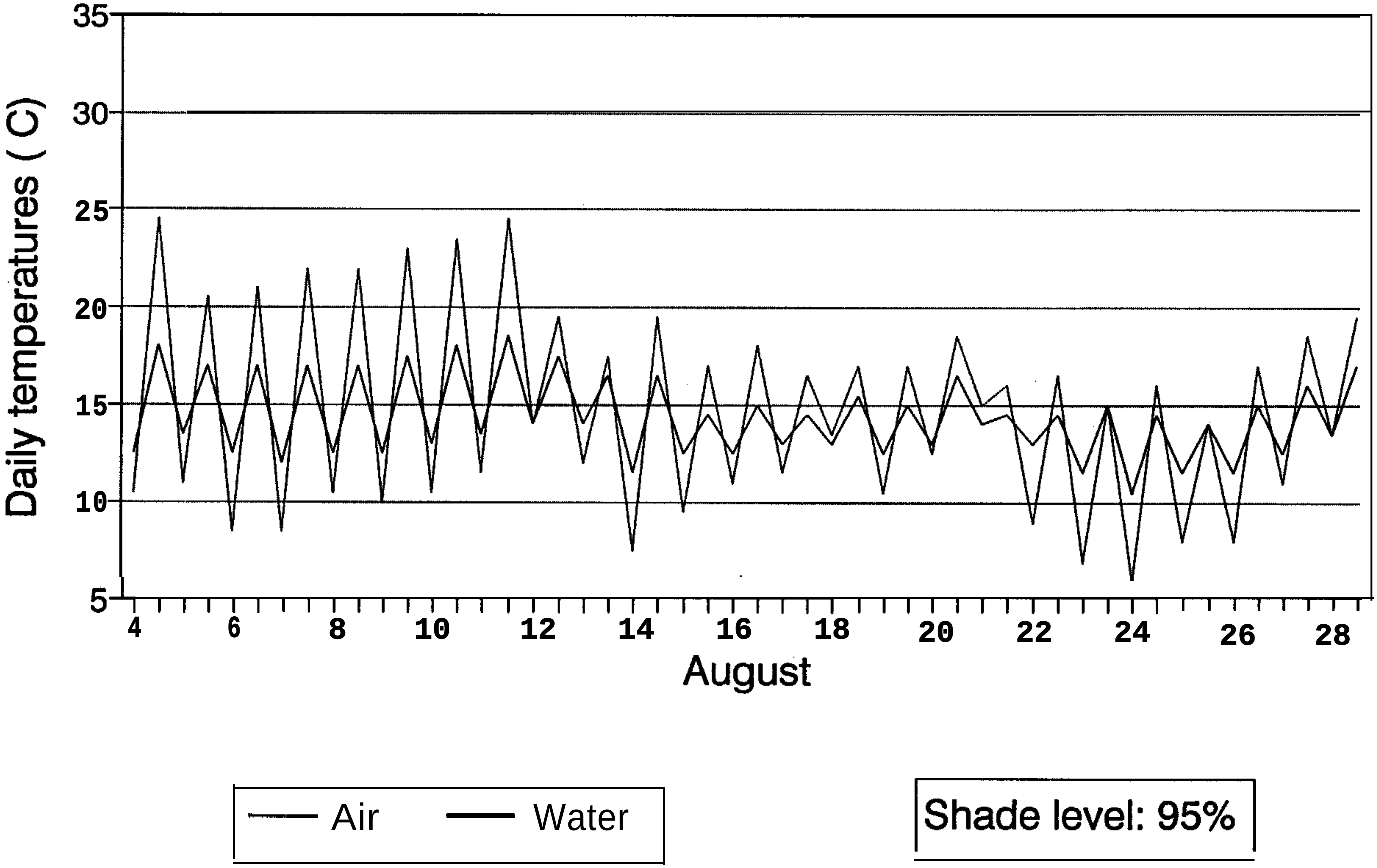
Shade level : 95%

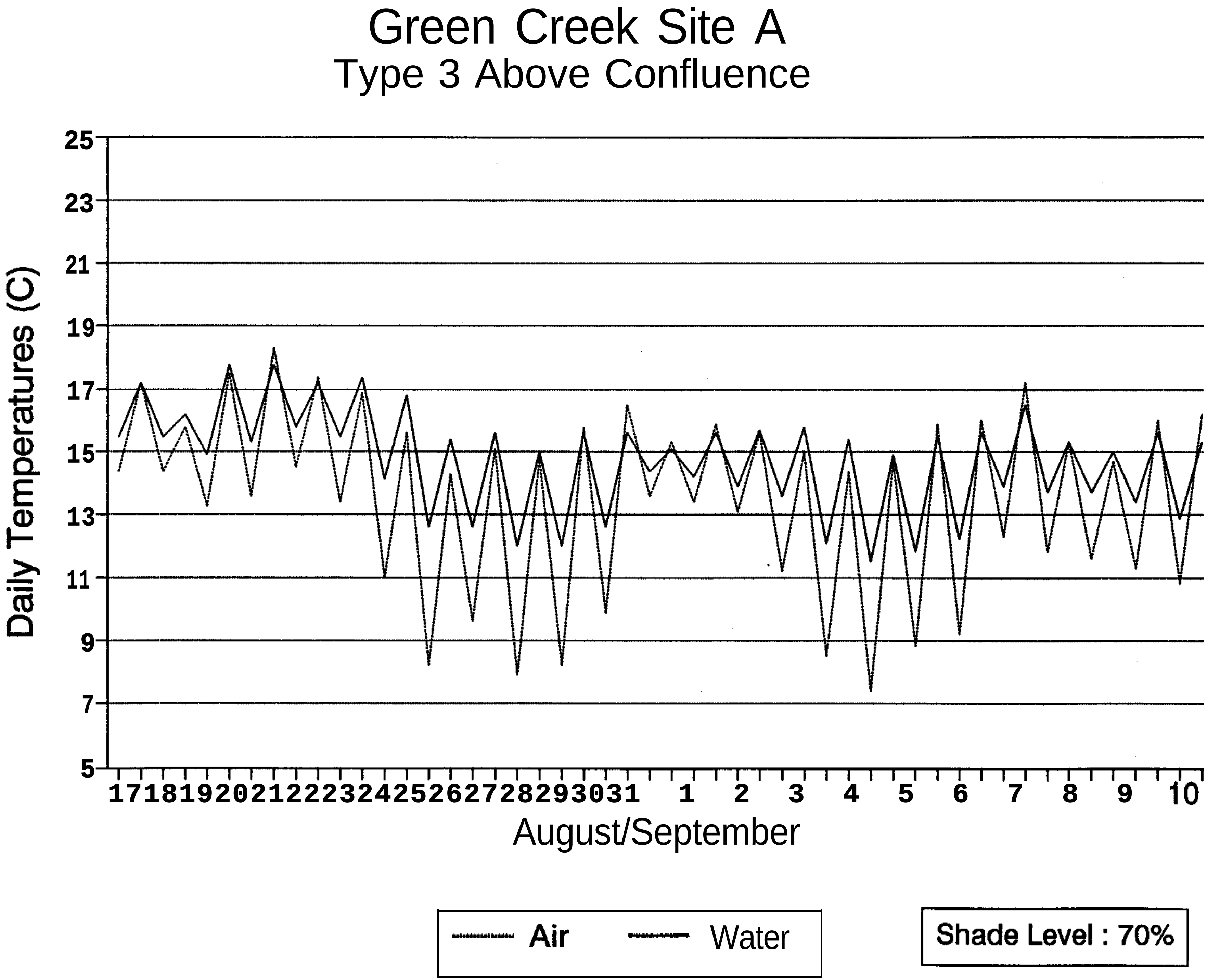
Abernathy Cr. Tributary Site E

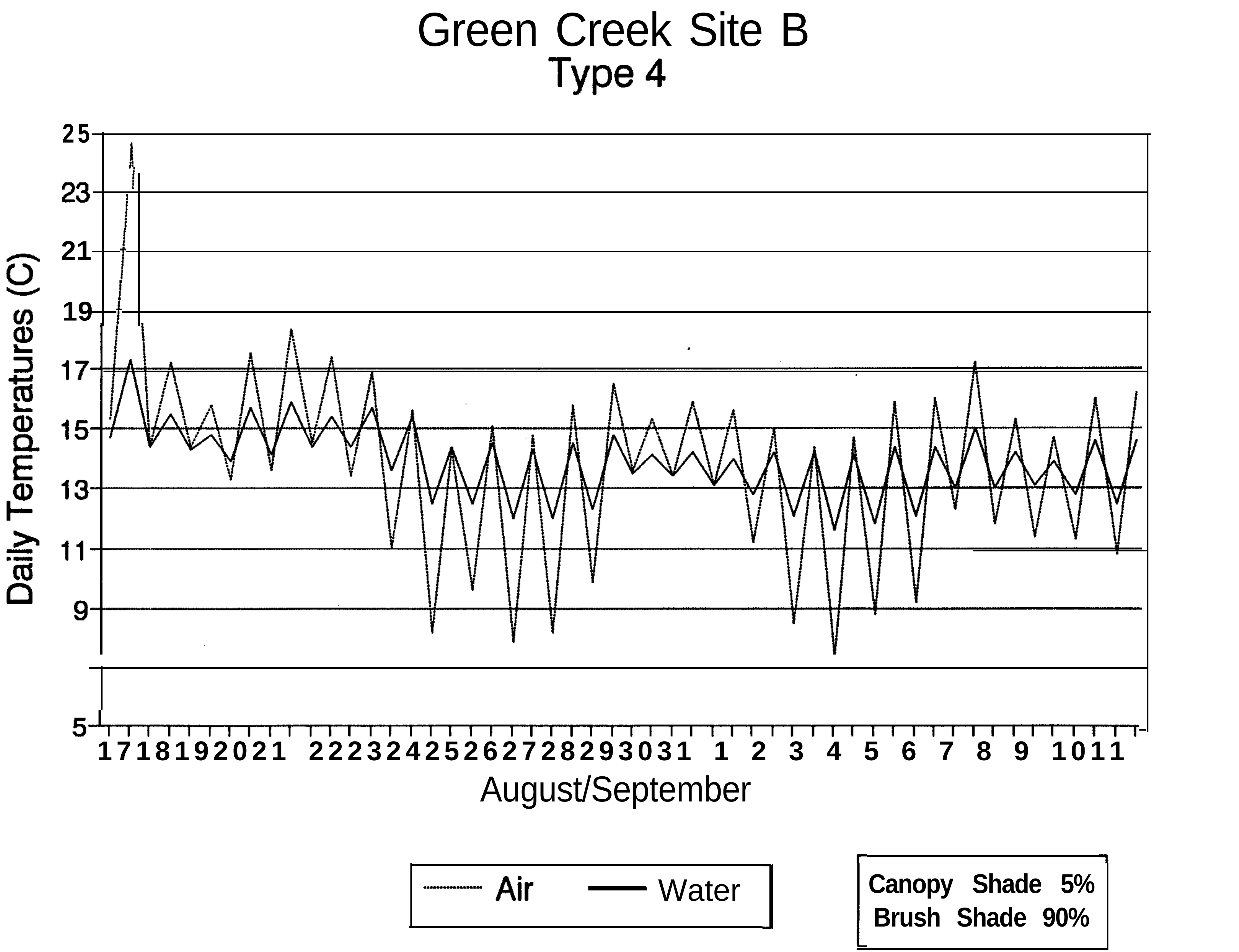
Type 3 within RMZ



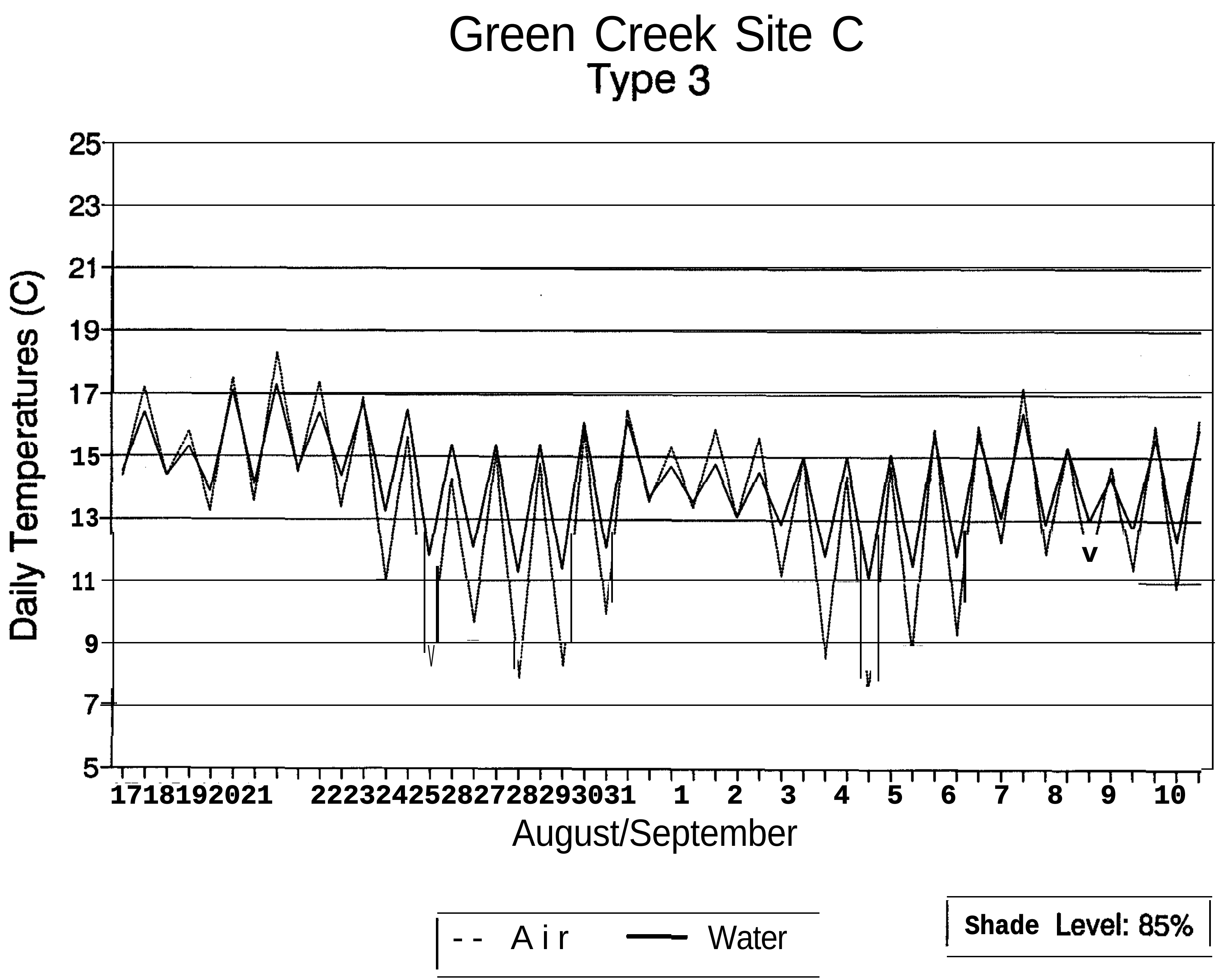
Abernathy Cr. Tributary Site F
Type 3 within RMZ



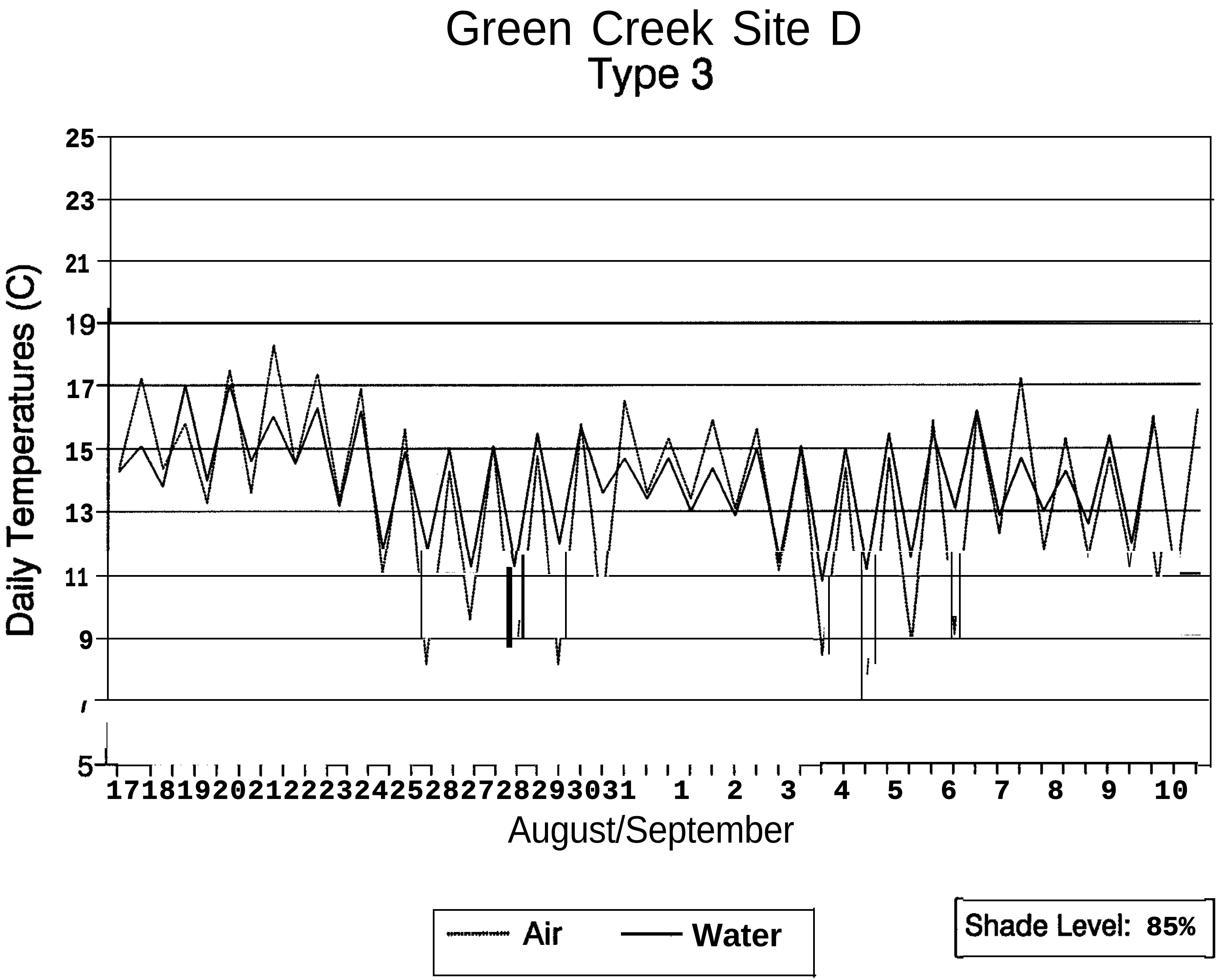

Green Creek Site A
Type 3 Above Confluence
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
7
5
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10
August/September
Air
Water
Shade Level : 70%



Green Creek Site B
Type 4
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
5
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10 11
August/September
Air
Water
Canopy Shade 5%
Brush Shade 90%

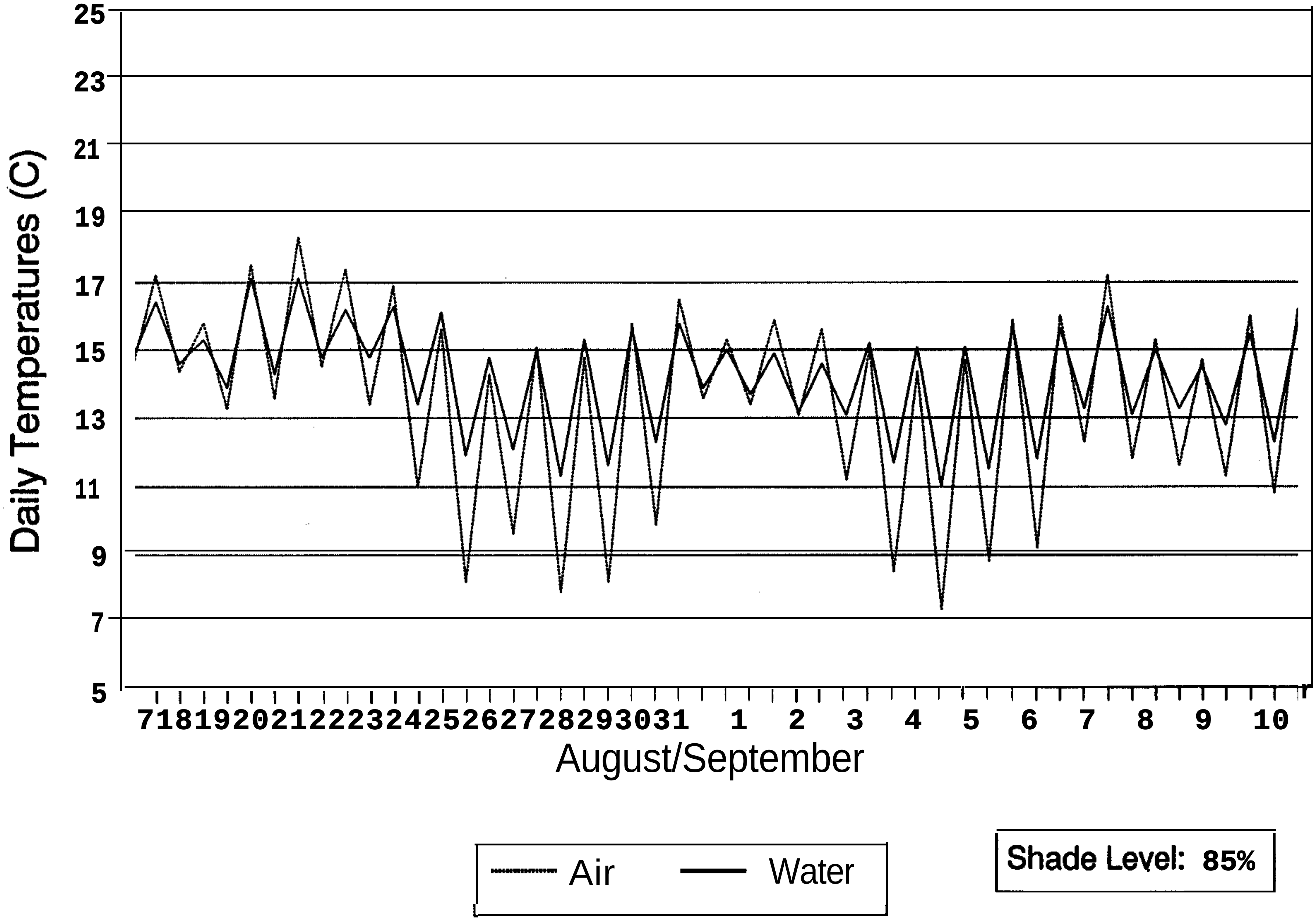


Green Creek Site C
Type 3
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
7
5
17 18 19 20 21 22 23 24 25 28 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10
August/September
-- Air
Water
Shade Level: 85%

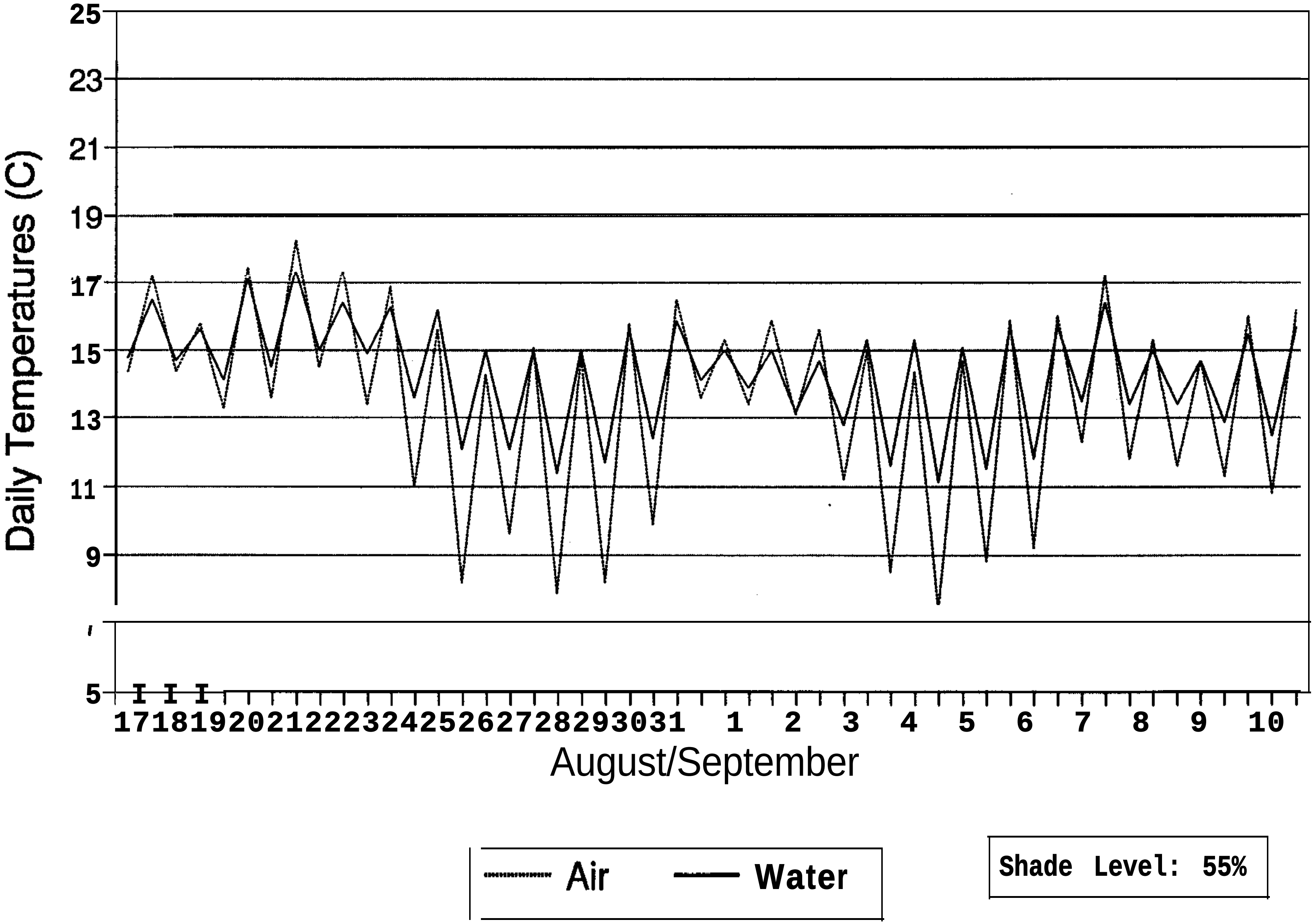


Green Creek Site D
Type 3
Daily Temperatures (C)
25
23
21
19
17
15
13
11
9
7
5
17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 1 2 3 4 5 6 7 8 9 10
August/September
Air
Water
Shade Level: 85%

Green Creek Site E
Type 3

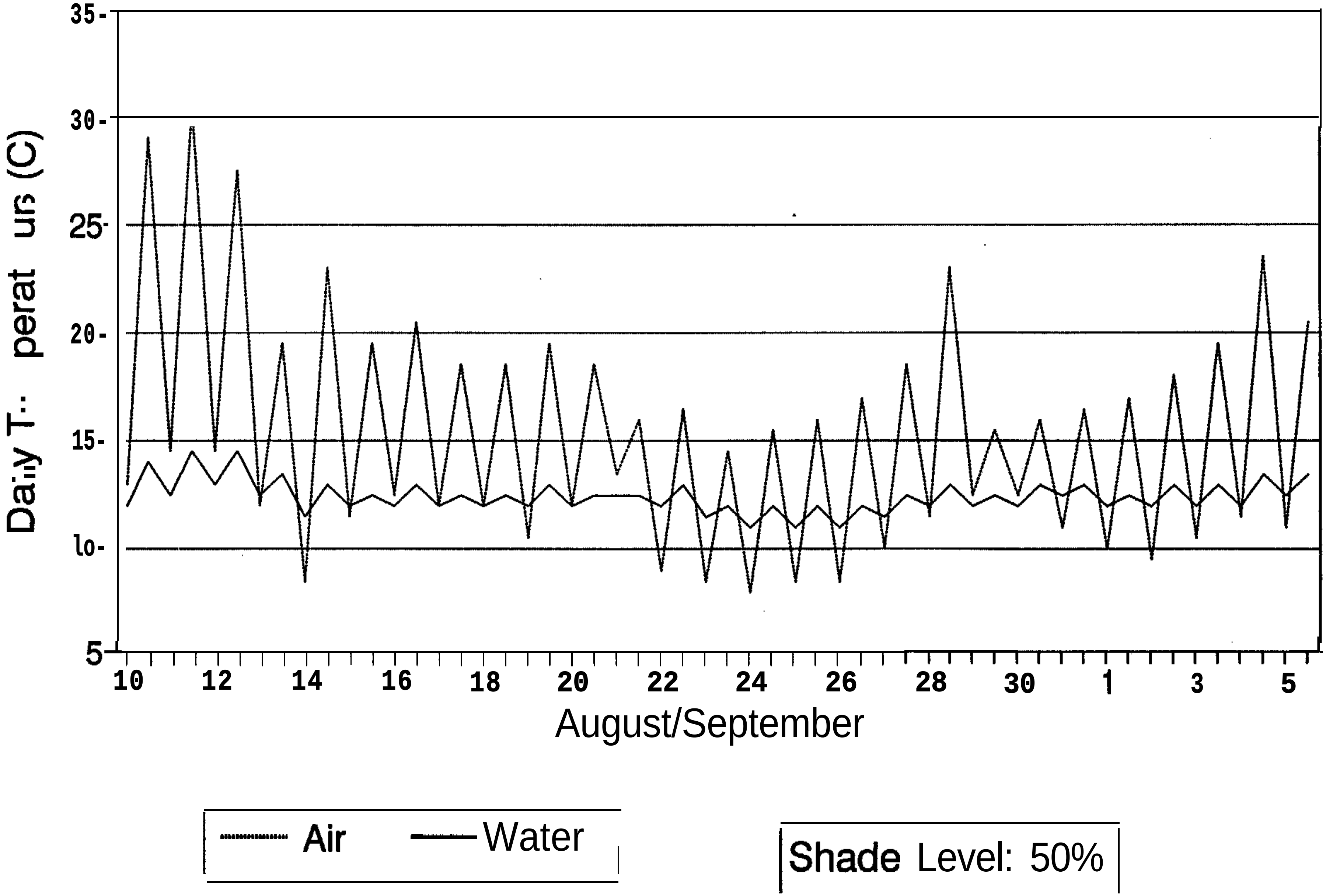


Green Creek Site F
Type 3

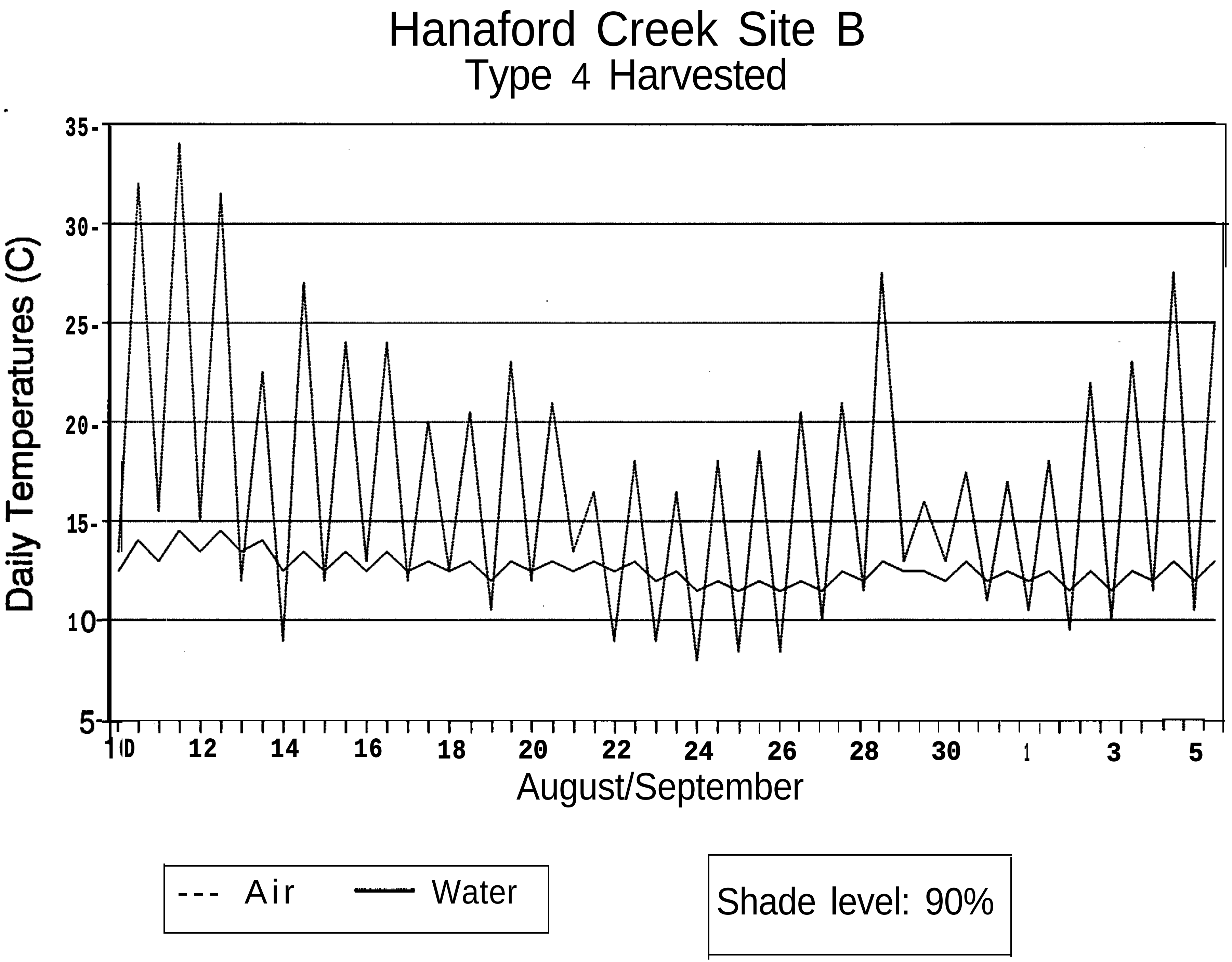


Hanaford Creek Site A

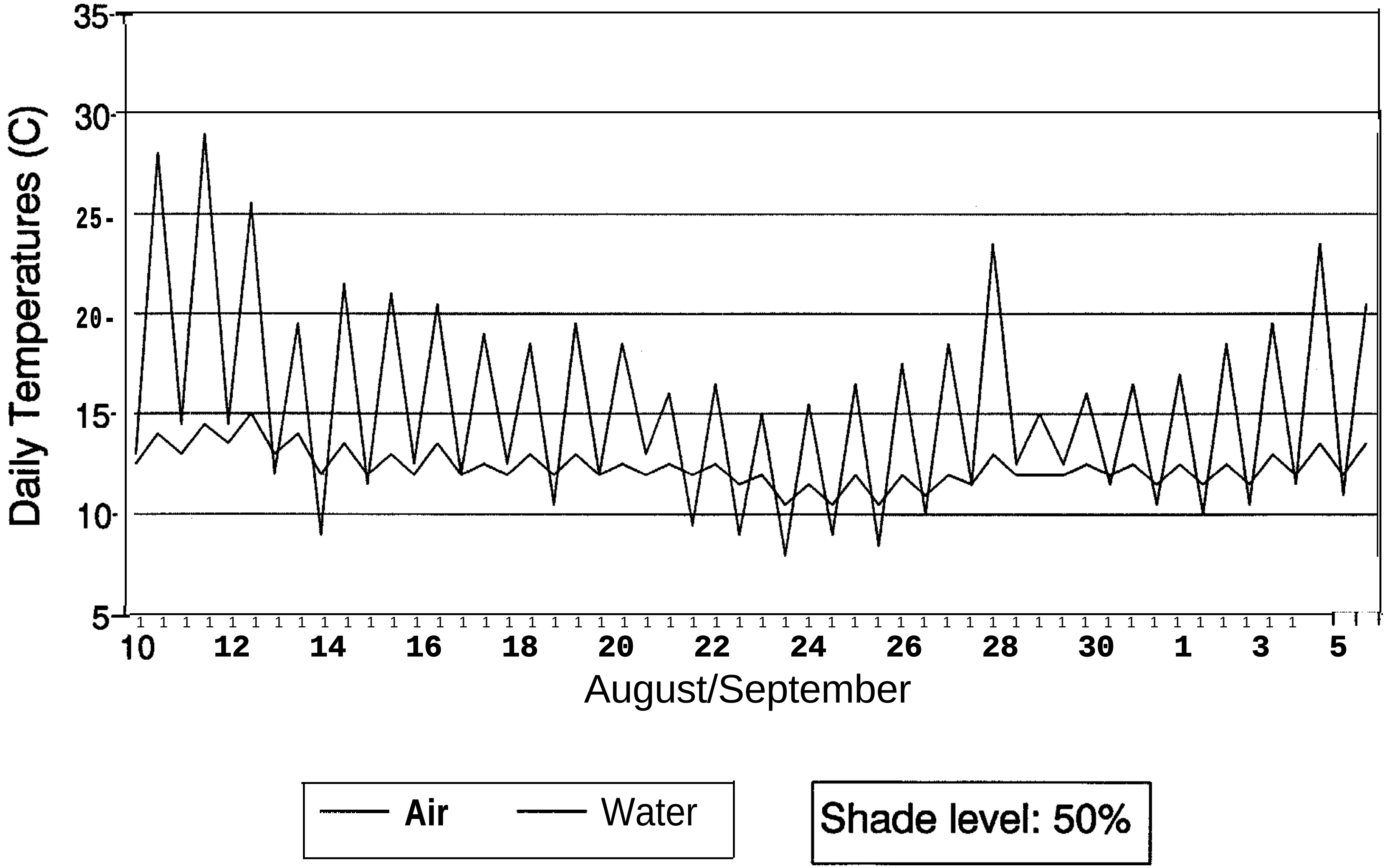
Type 3, above tributaries



Shade Level: 50%

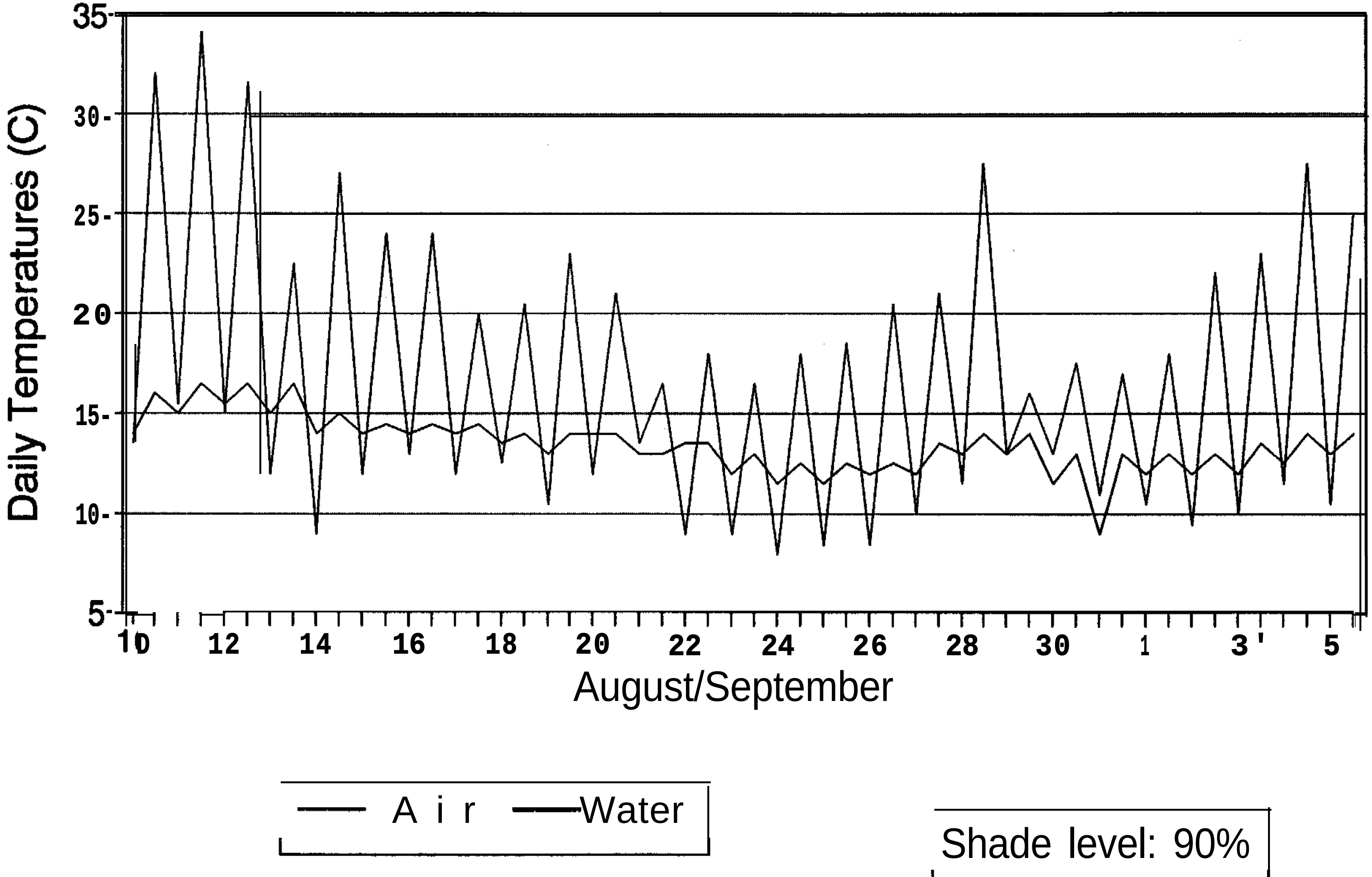

Hanaford Creek Site B
Type 4 Harvested
Daily Temperatures (C)
35
30
25
20
15
10
5
10
12
14
16
18
20
22
24
26
28
30
1
3
5
August/September
--- Air
Water
Shade level: 90%

Hanaford Creek Site C
Type 3, Mainstem between Tributaries



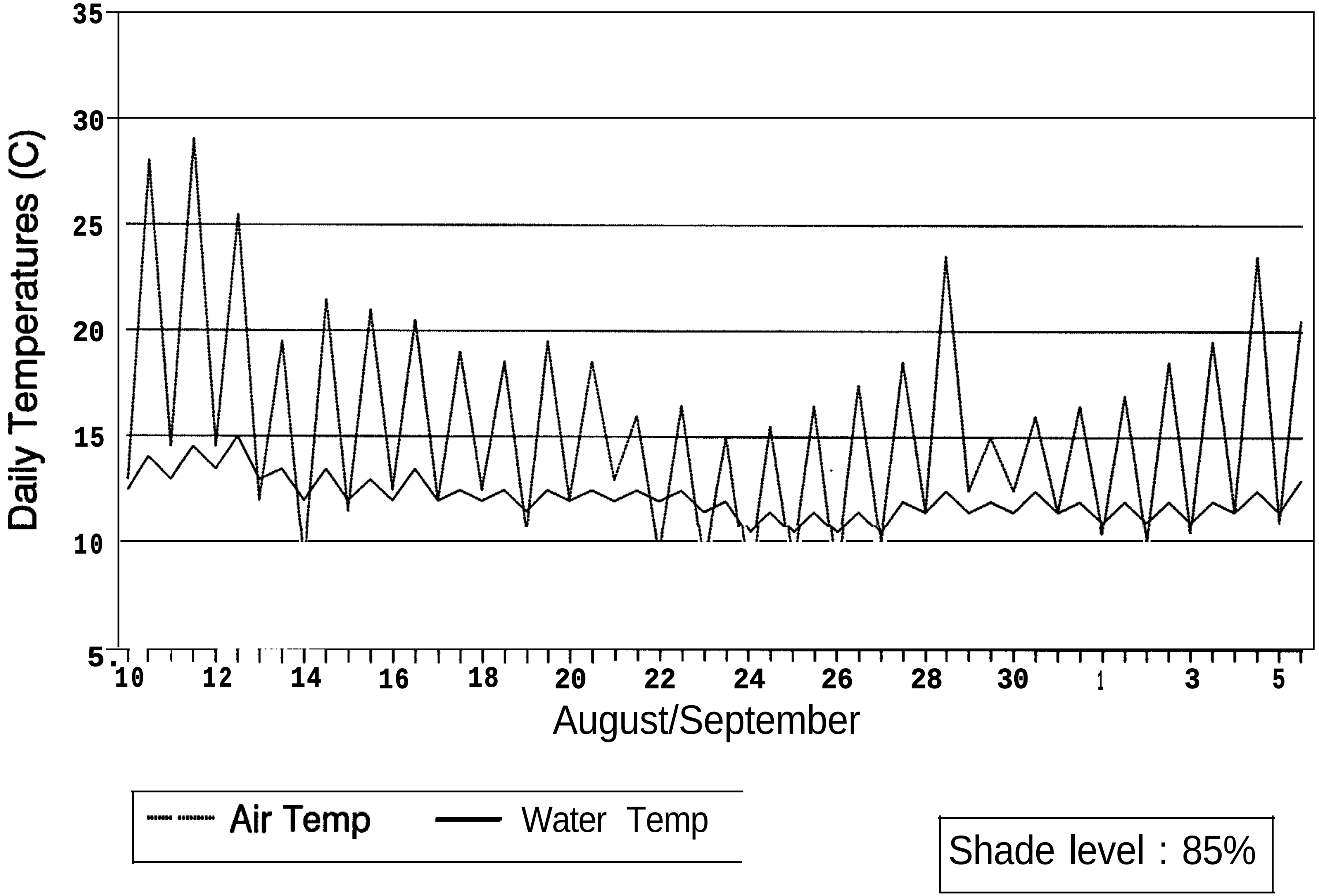
Shade level: 50%

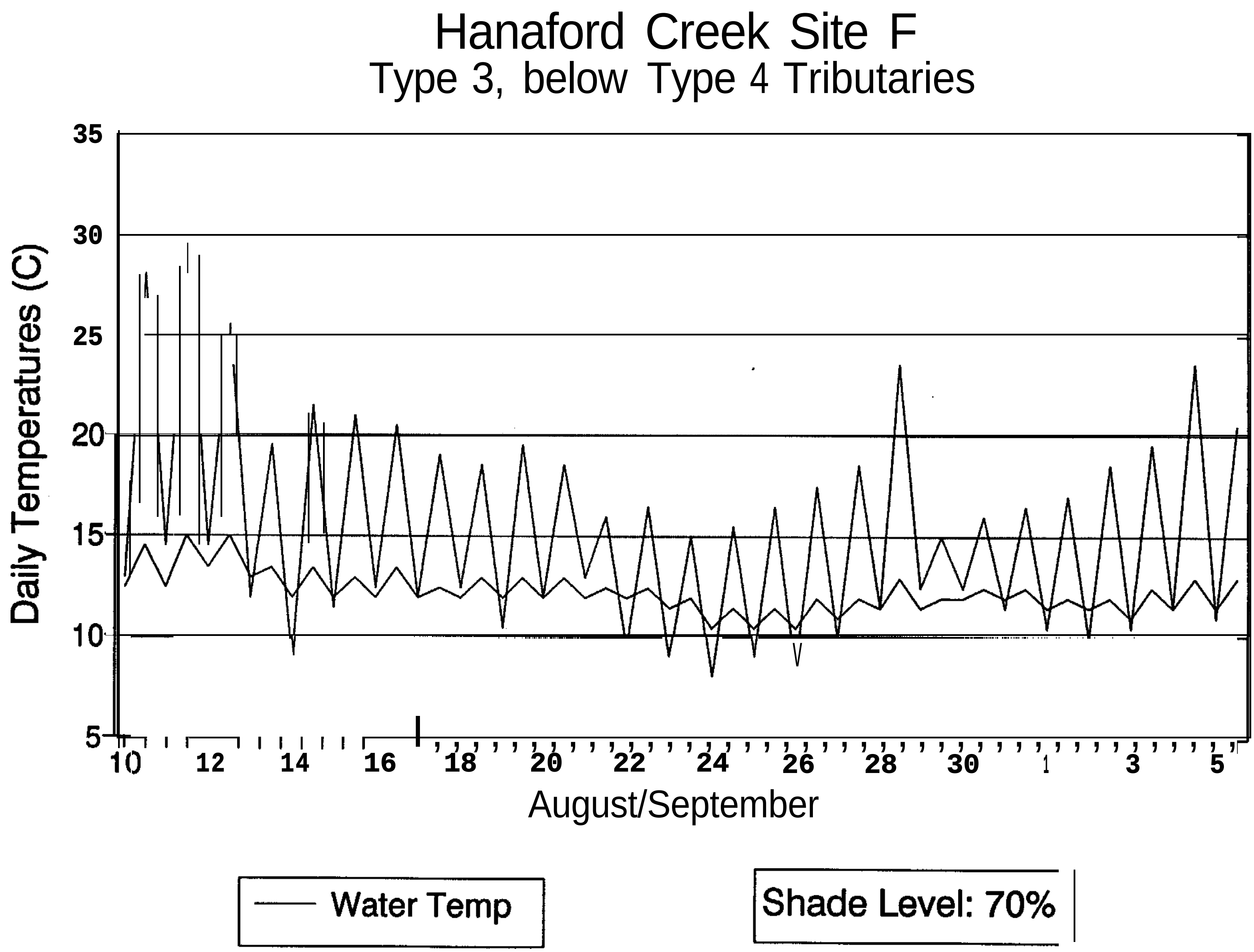
Hanaford Creek Site D
Type 4 Harvested



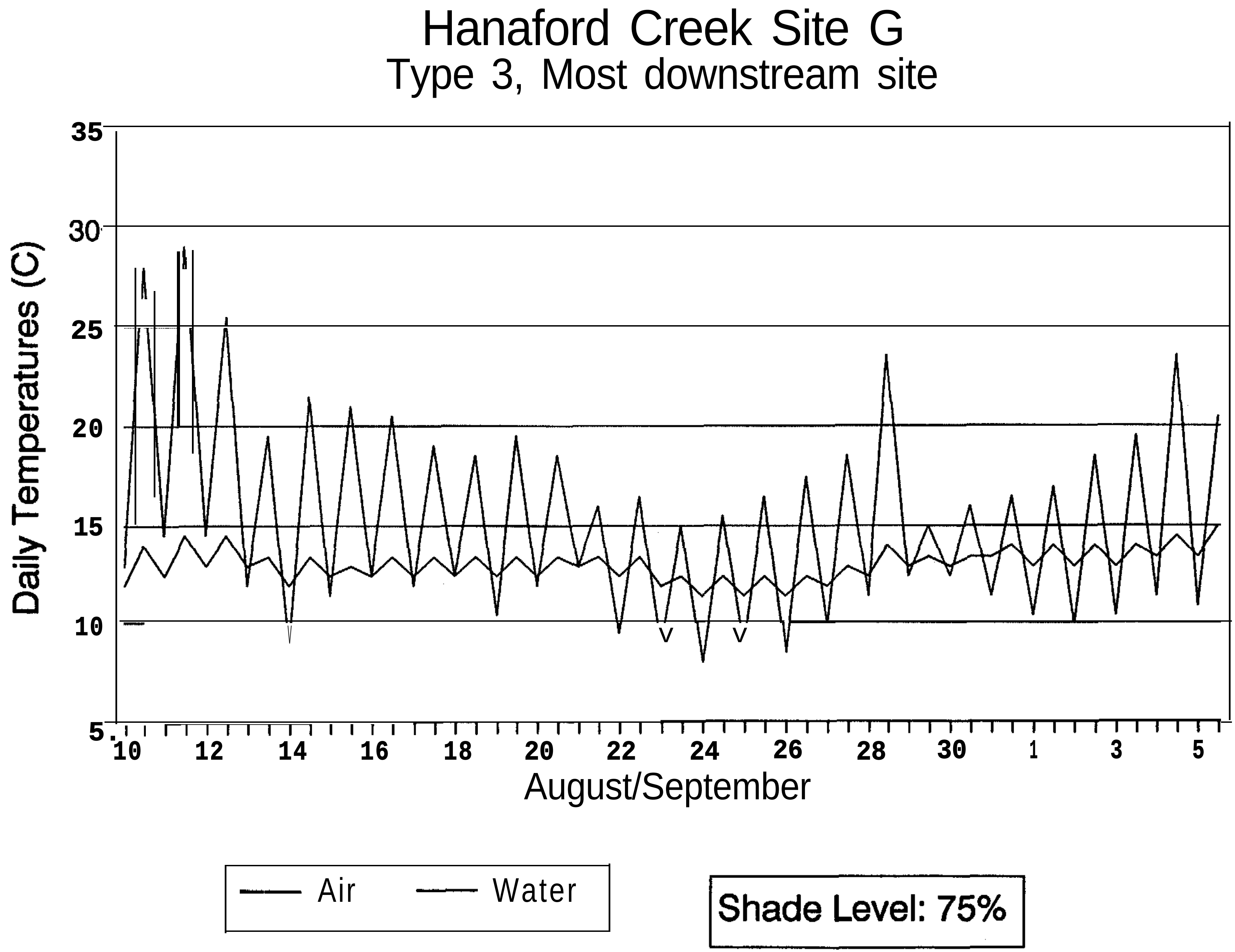
Shade level: 90%

Hanaford Creek Site E
Type 3, below both Type 4 Tributaries

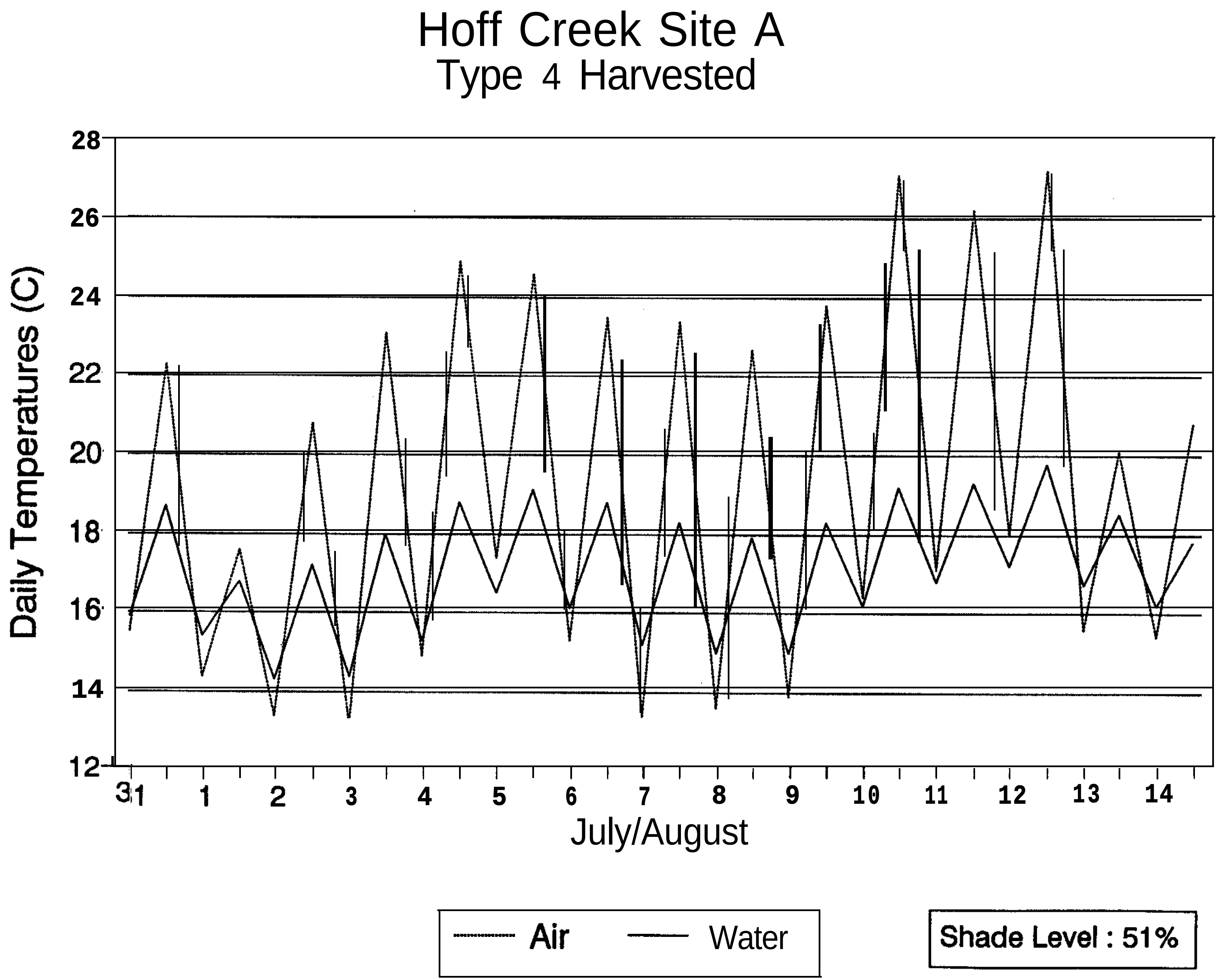




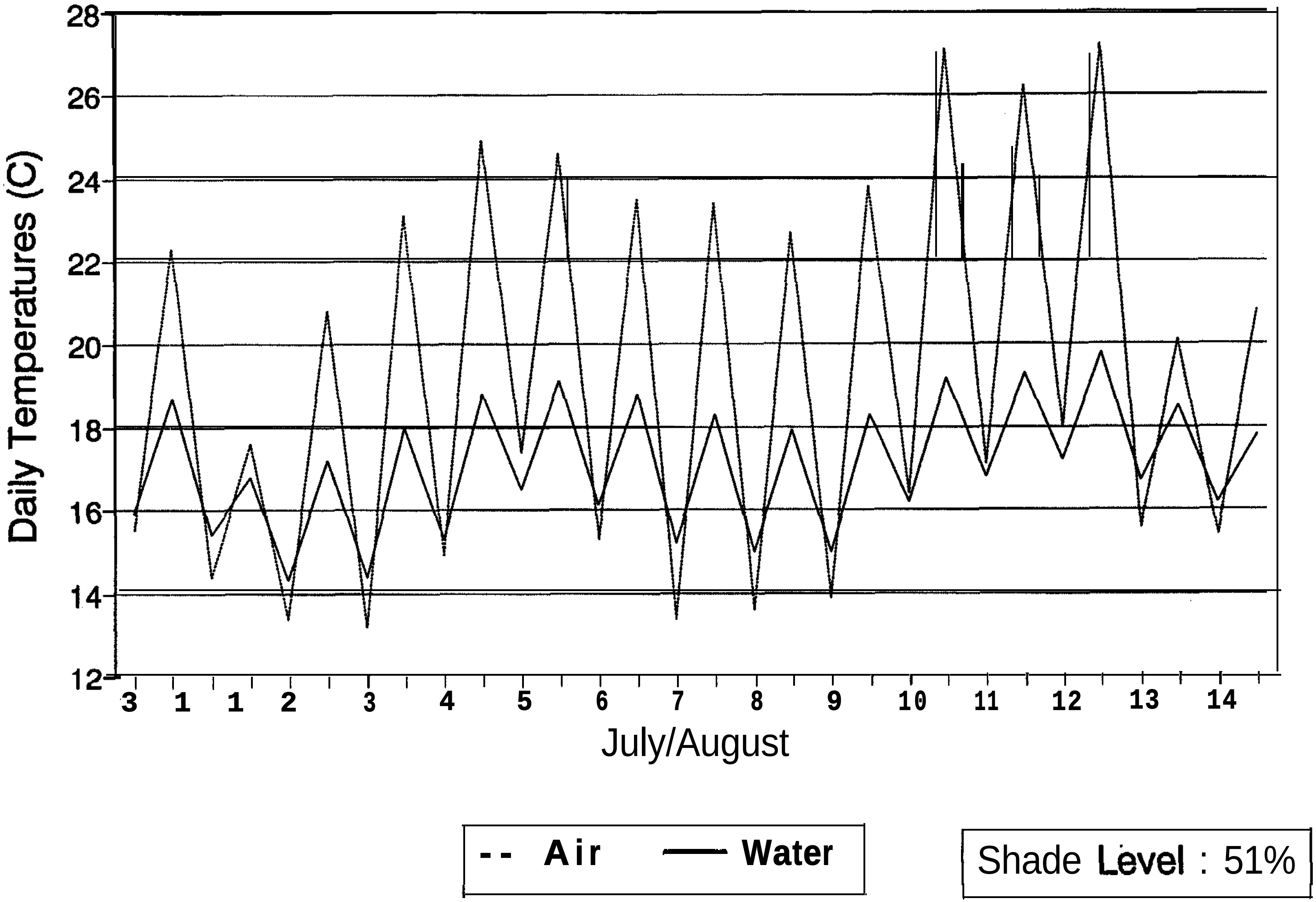
Hanaford Creek Site F
Type 3, below Type 4 Tributaries
Daily Temperatures (C)
35
30
25
20
15
10
5
10
12
14
16
18
20
22
24
26
28
30
1
3
5
August/September
Water Temp
Shade Level: 70%

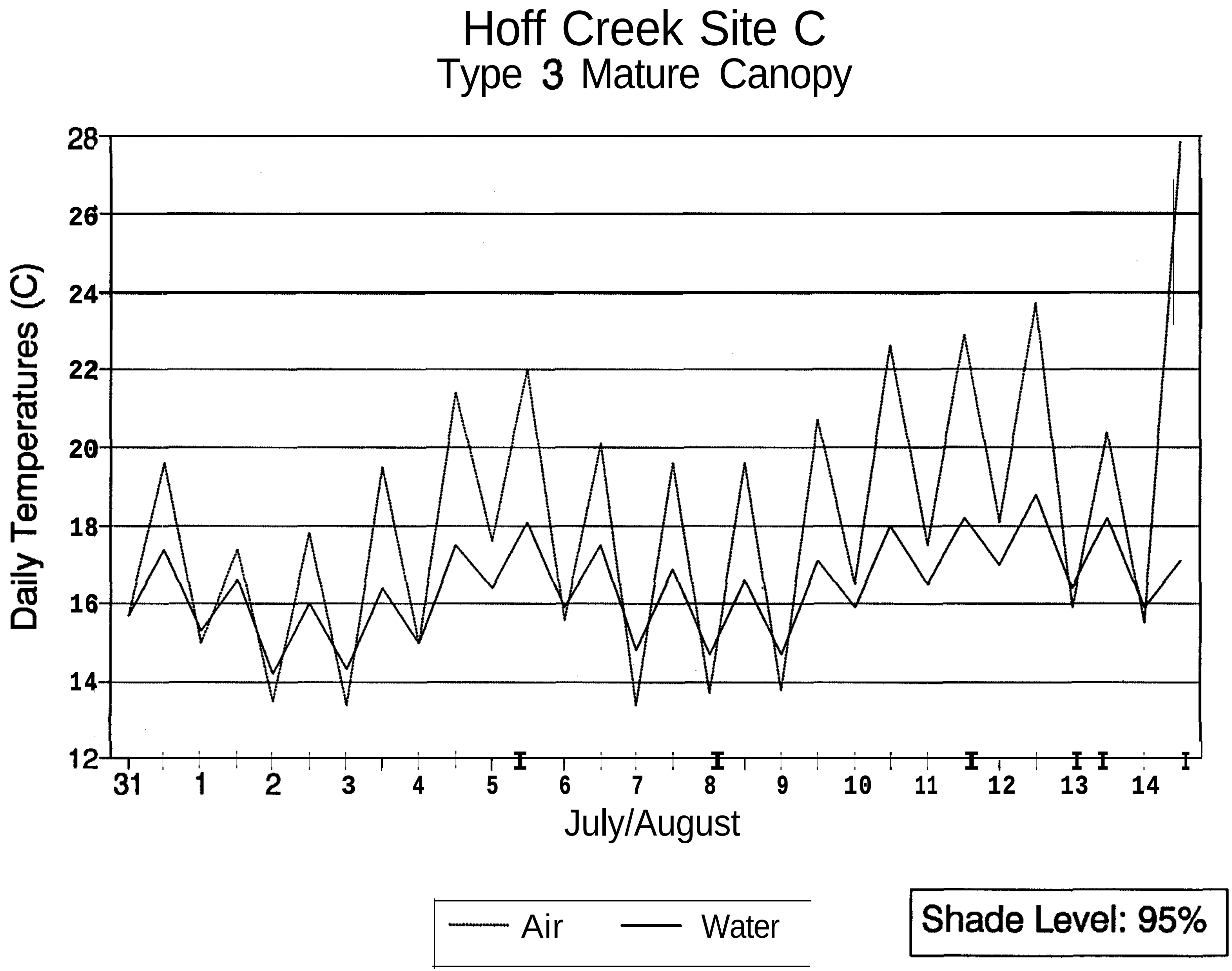


Hanaford Creek Site G
Type 3, Most downstream site
Daily Temperatures (C)
35
30
25
20
15
10
5
10
12
14
16
18
20
22
24
26
28
30
1
3
5
August/September
Air
Water
Shade Level: 75%

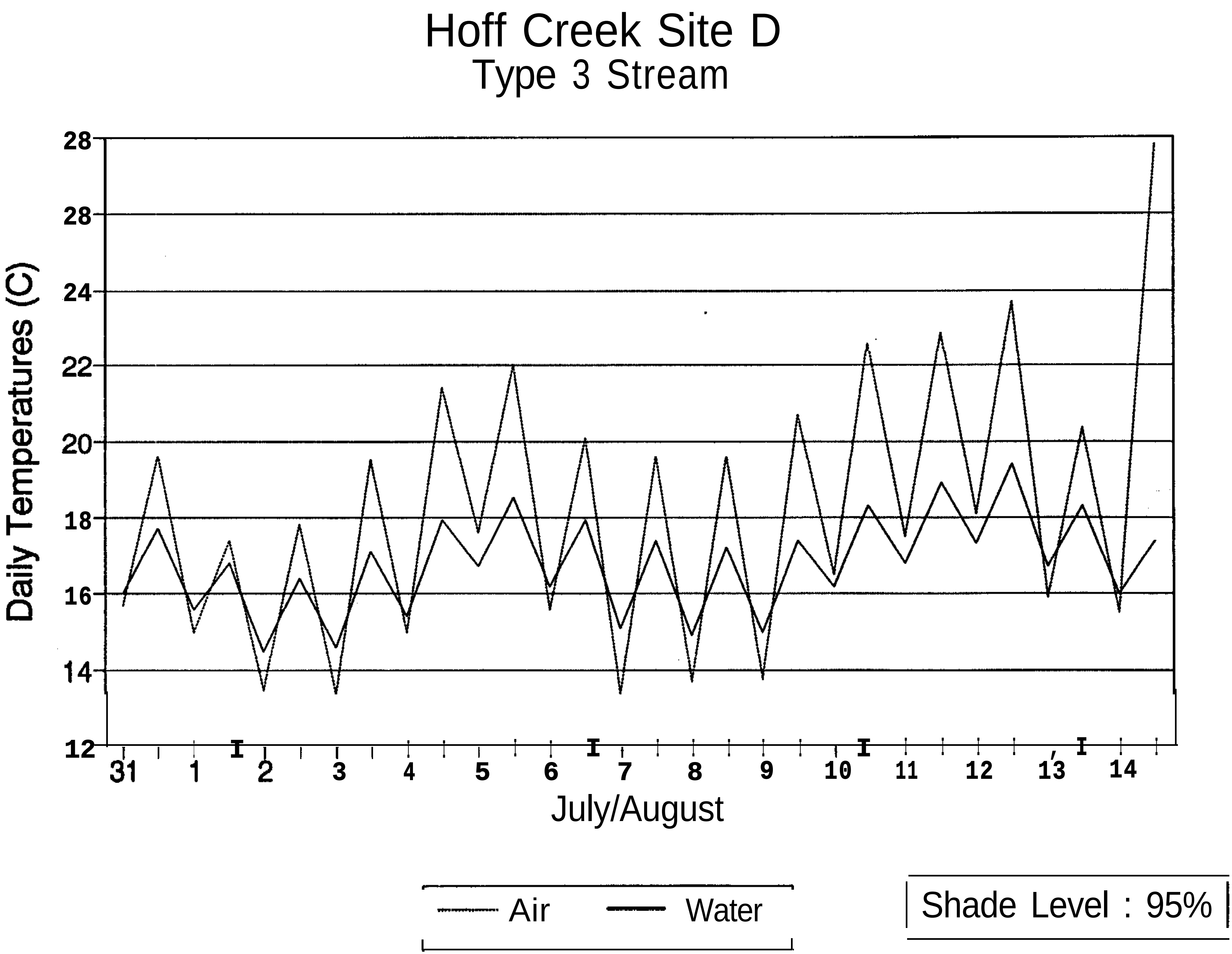

Hoff Creek Site A
Type 4 Harvested
Daily Temperatures (C)
28
26
24
22
20
18
16
14
12
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
July/August
Air
Water
Shade Level : 51%

Hoff Creek Site B
Type 4 Harvested

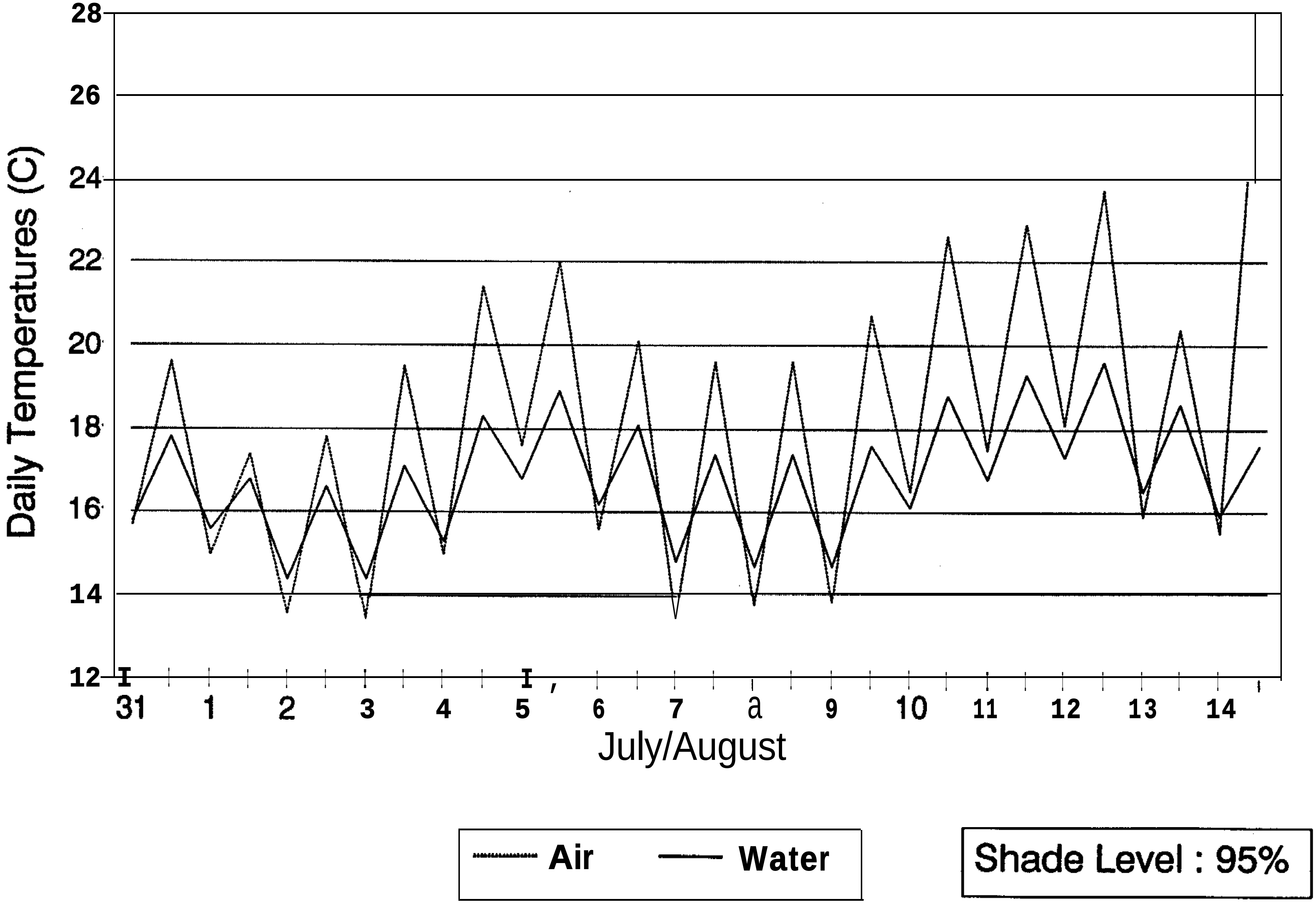


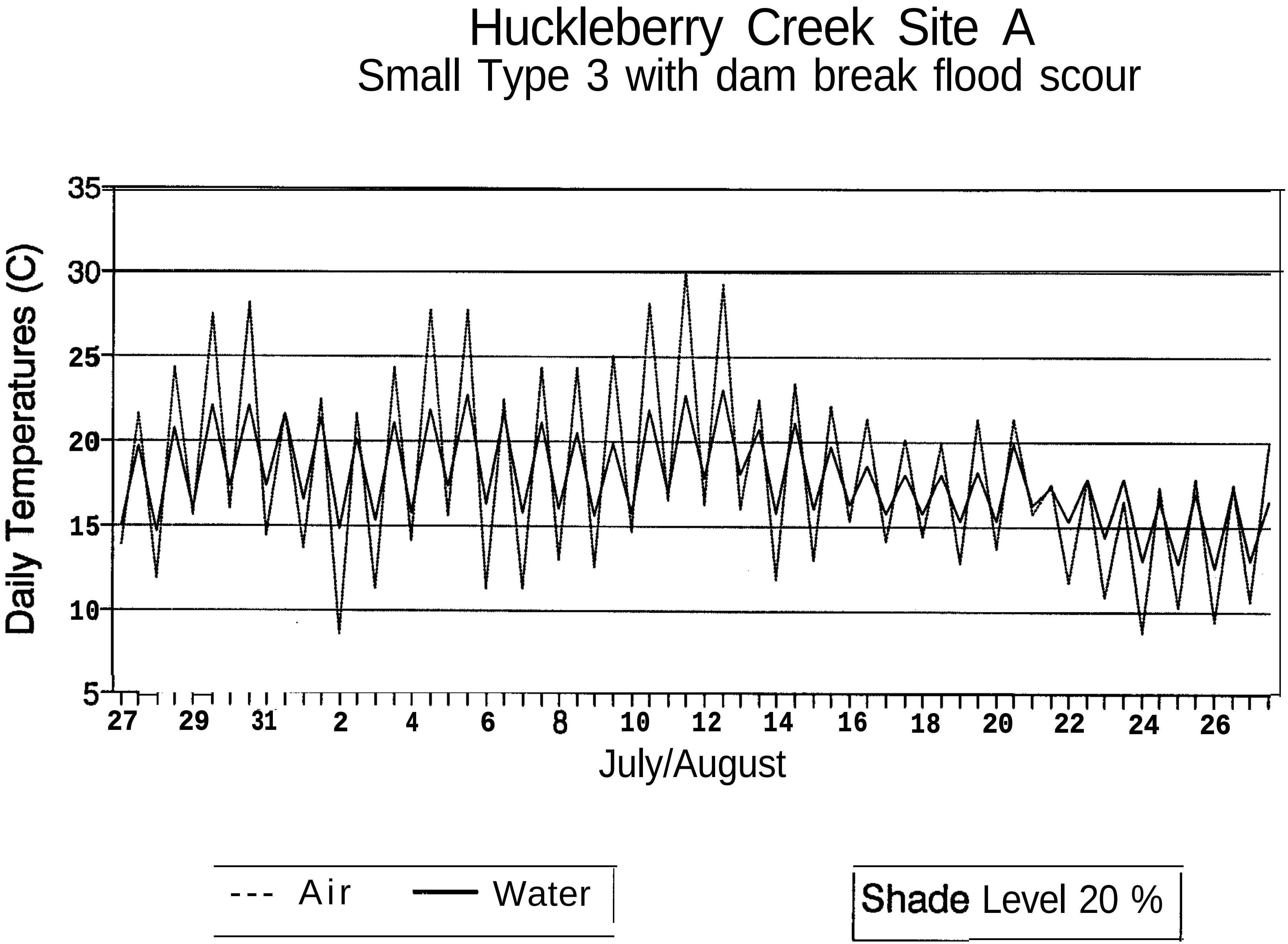


Hoff Creek Site C
Type 3 Mature Canopy
Daily Temperatures (C)
28
26
24
22
20
18
16
14
12
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
July/August
Air
Water
Shade Level: 95%

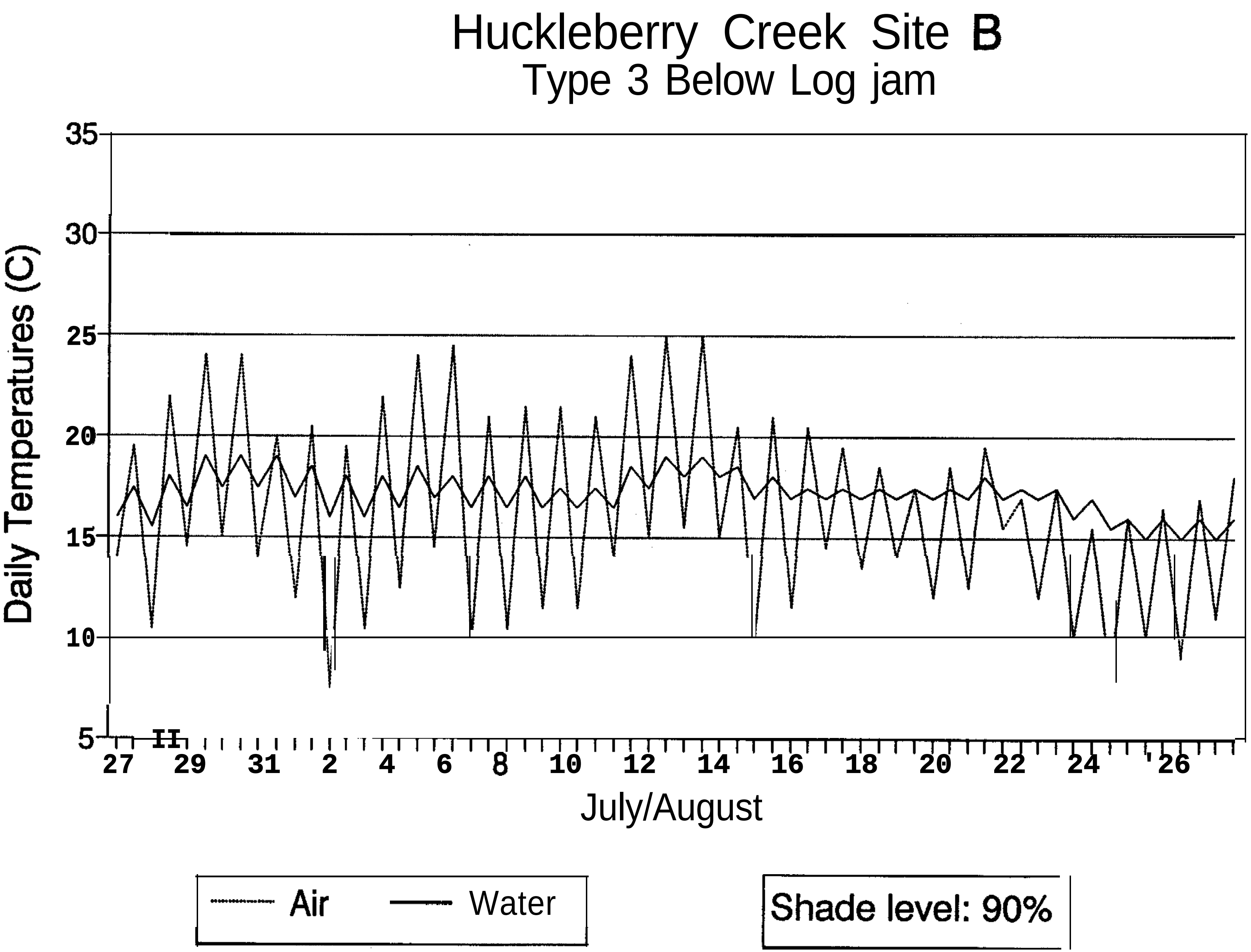

Hoff Creek Site D
Type 3 Stream
Daily Temperatures (C)
28
28
24
22
20
18
16
14
12
31
1
2
3
4
5
6
7
8
9
10
11
12
13
14
July/August
Air
Water
Shade Level : 95%

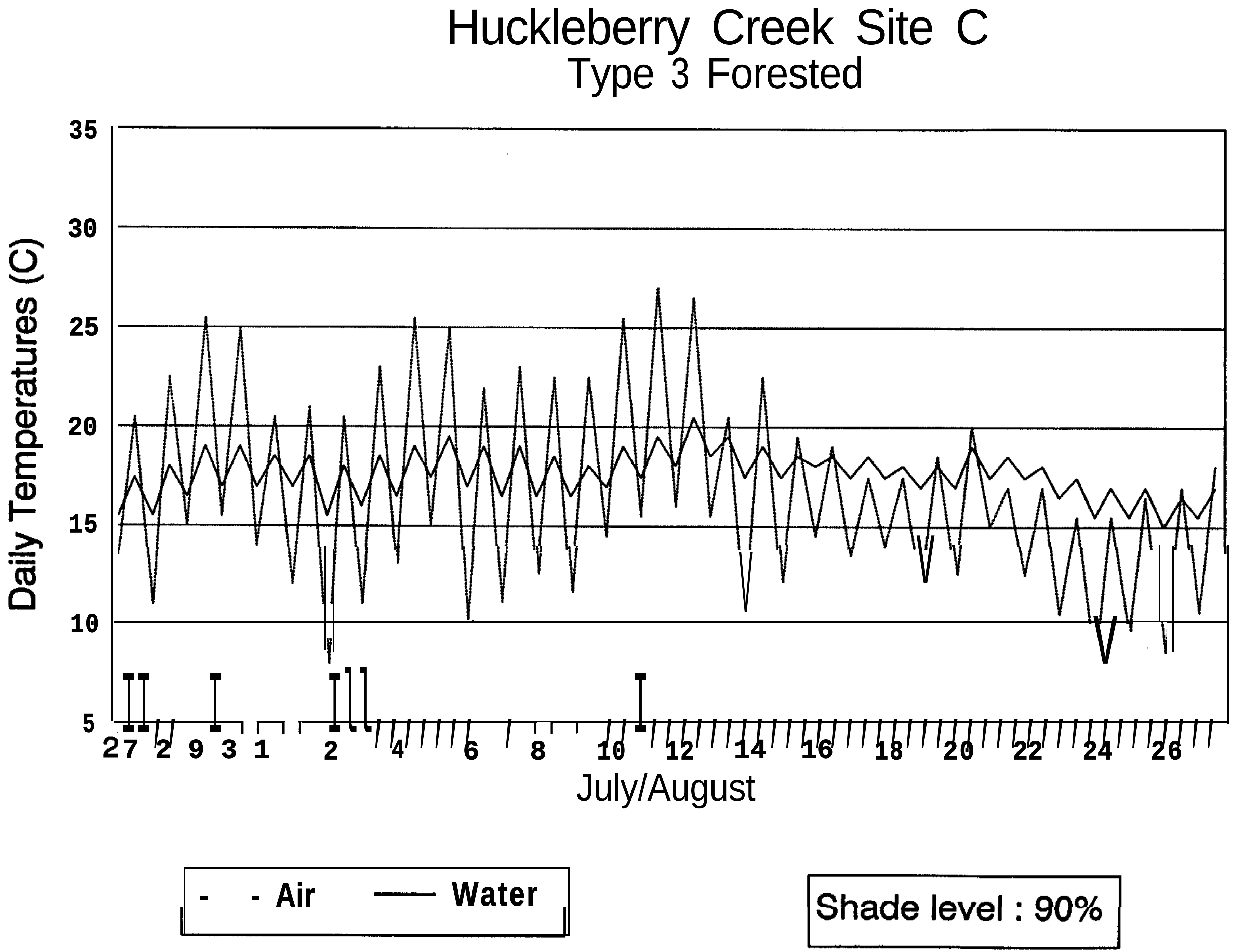
Hoff Creek Site E
Type 3 Stream



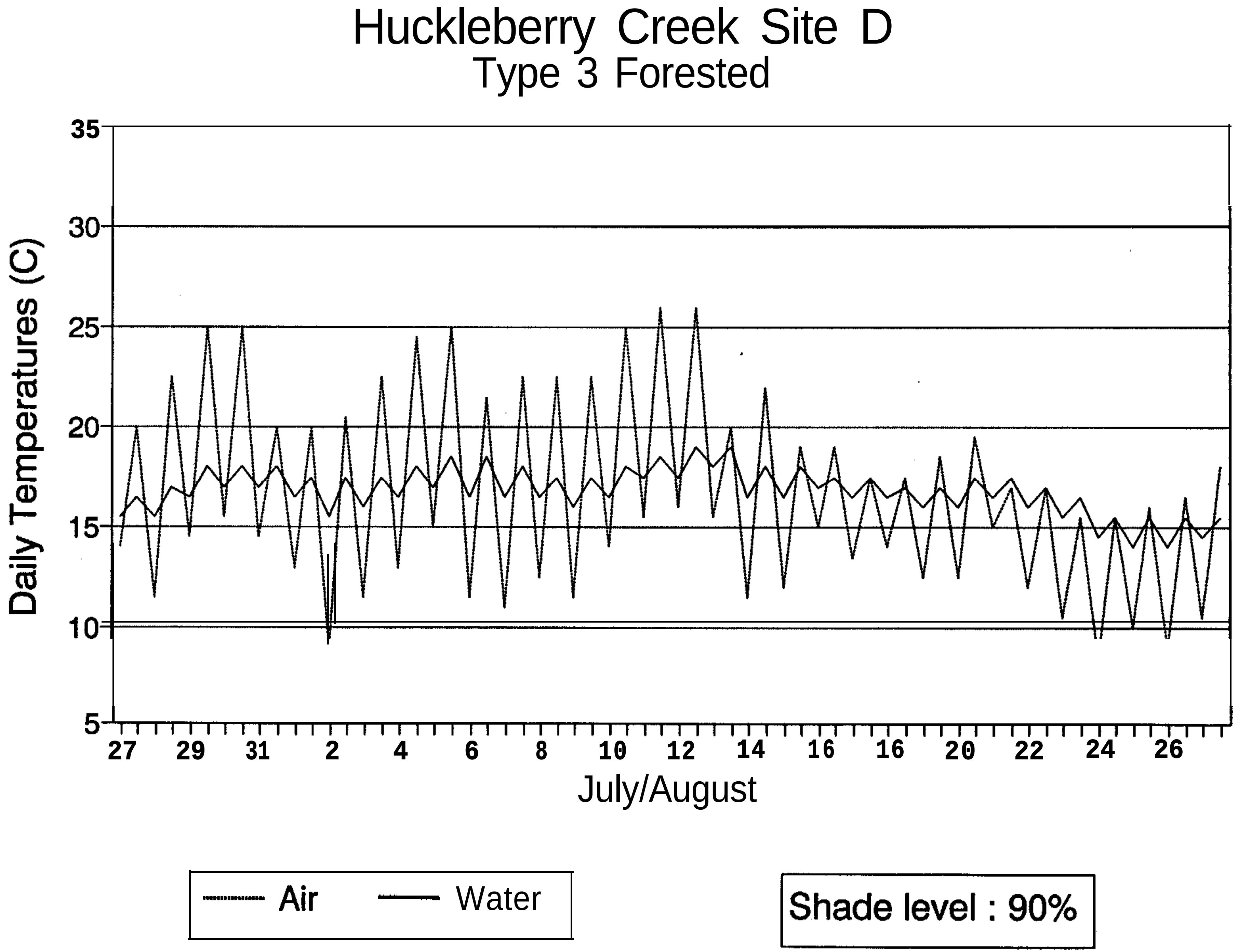


Huckleberry Creek Site A
Small Type 3 with dam break flood scour
Daily Temperatures (C)
35
30
25
20
15
10
5
27
29
31
2
4
6
8
10
12
14
16
18
20
22
24
26
July/August
--- Air
Water
Shade Level 20 %

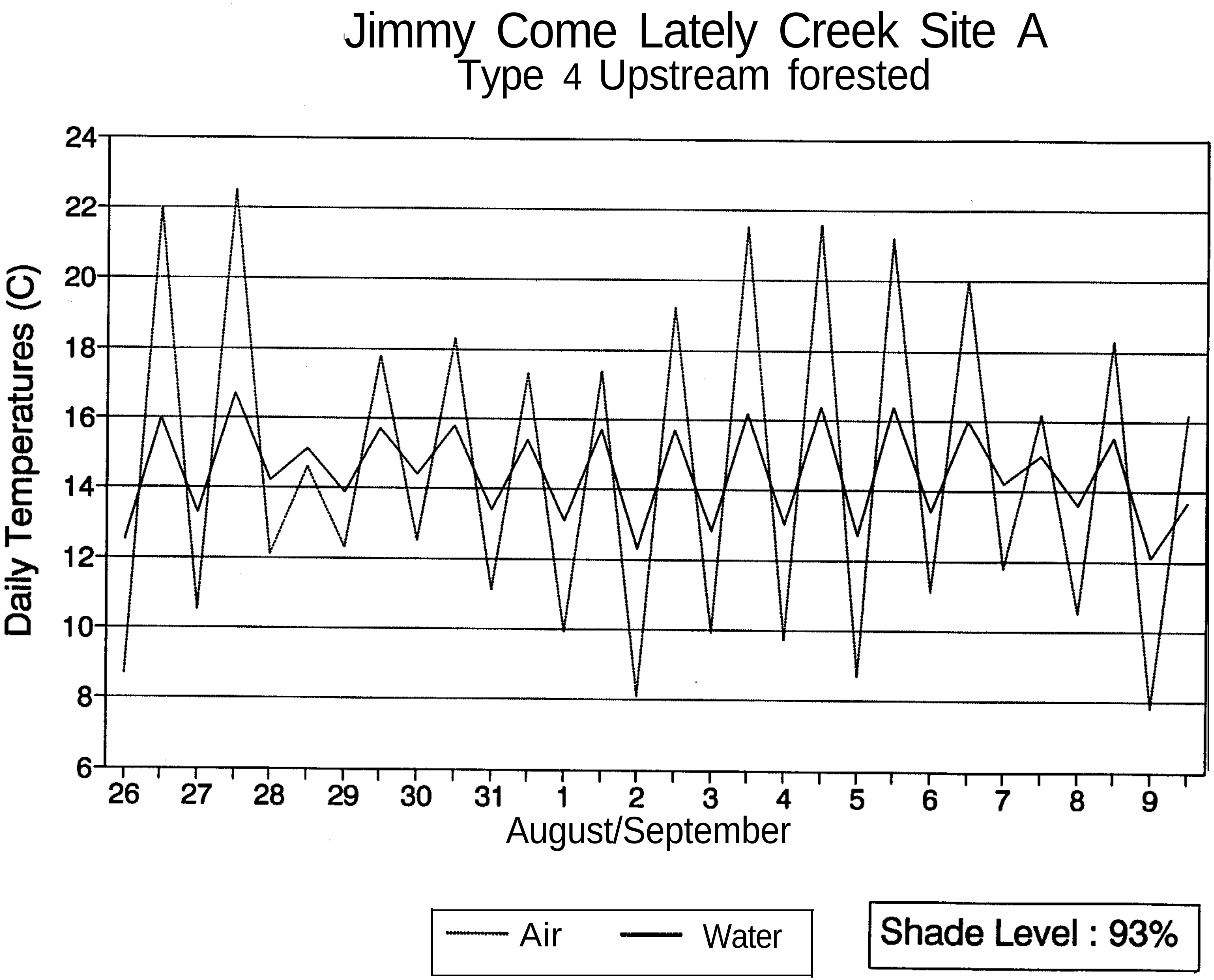

Huckleberry Creek Site B
Type 3 Below Log jam
35
30
25
20
15
10
5
Daily Temperatures (C)
27
29
31
2
4
6
8
10
12
14
16
18
20
22
24
26
July/August
Air
Water
Shade level: 90%



Huckleberry Creek Site C
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
27 2 9 3 1 2 4 6 8 10 12 14 16 18 20 22 24 26
July/August
- - Air
Water
Shade level : 90%

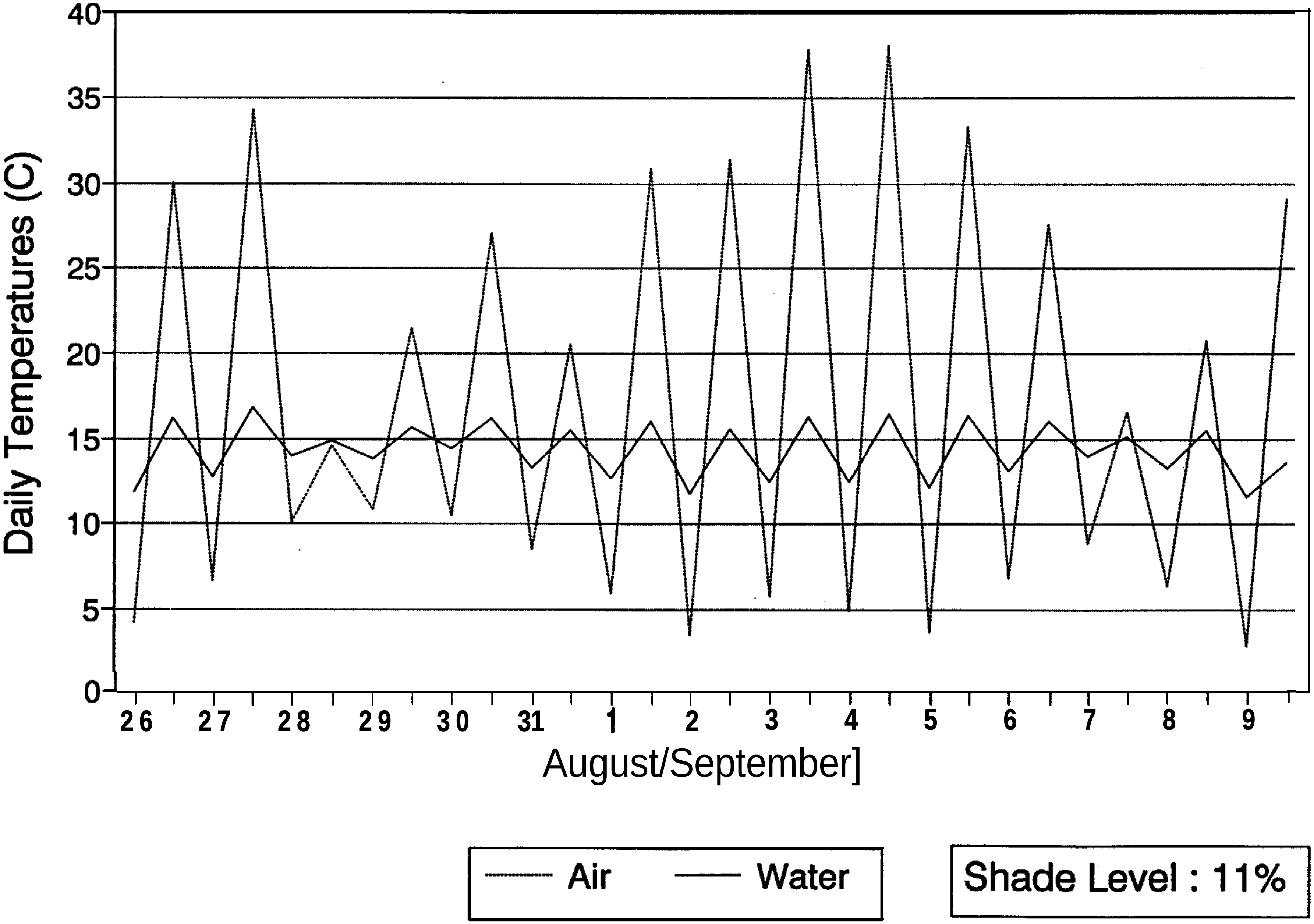


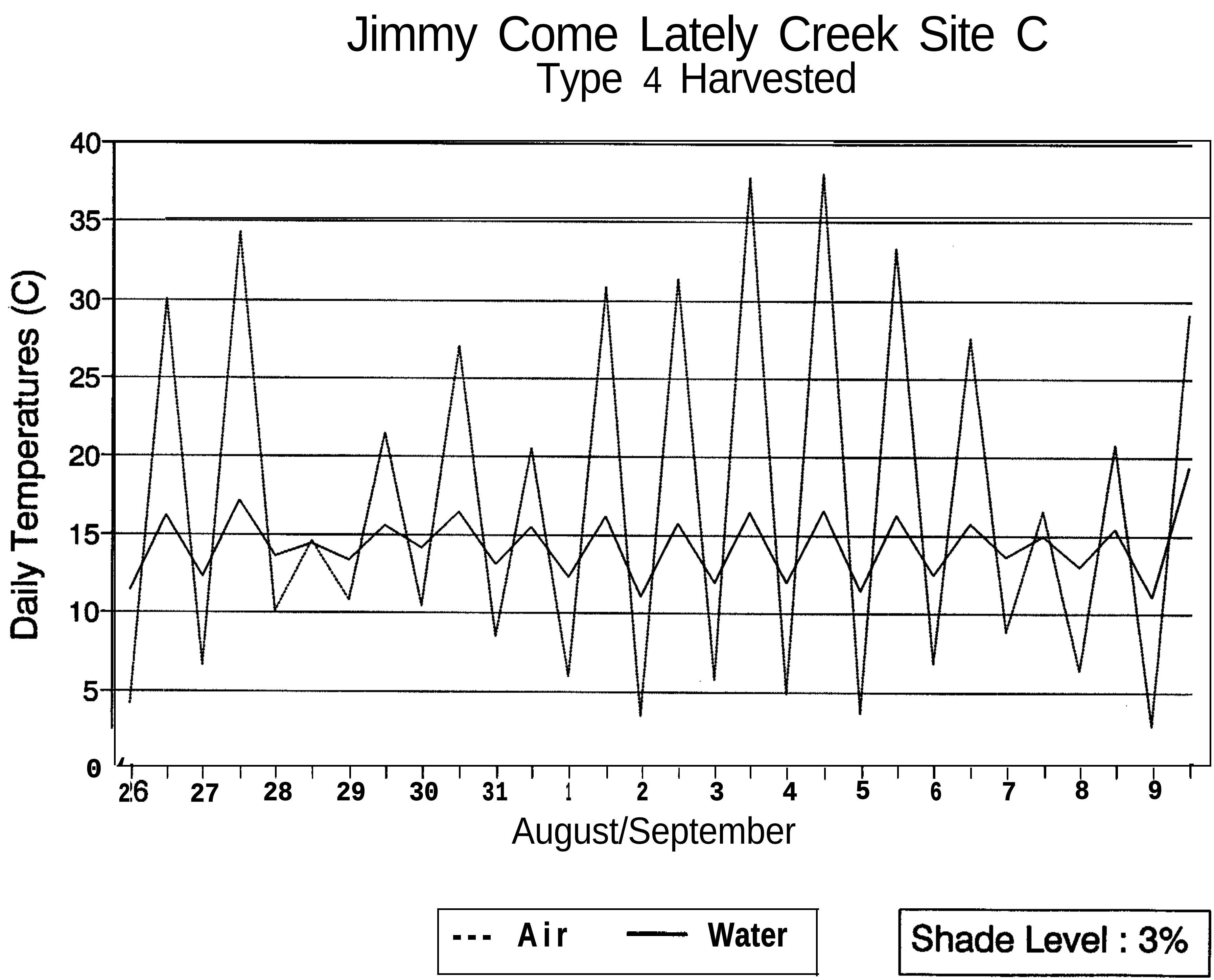
Huckleberry Creek Site D
Type 3 Forested
35
30
25
20
15
10
5
Daily Temperatures (C)
27
29
31
2
4
6
8
10
12
14
16
16
20
22
24
26
July/August
Air
Water
Shade level : 90%



Jimmy Come Lately Creek Site A
Type 4 Upstream forested
Daily Temperatures (C)
24
22
20
18
16
14
12
10
8
6
26
27
28
29
30
31
1
2
3
4
5
6
7
8
9
August/September
Air
Water
Shade Level : 93%

Jimmy Come Lately Creek Site B
Type 4 Harvested

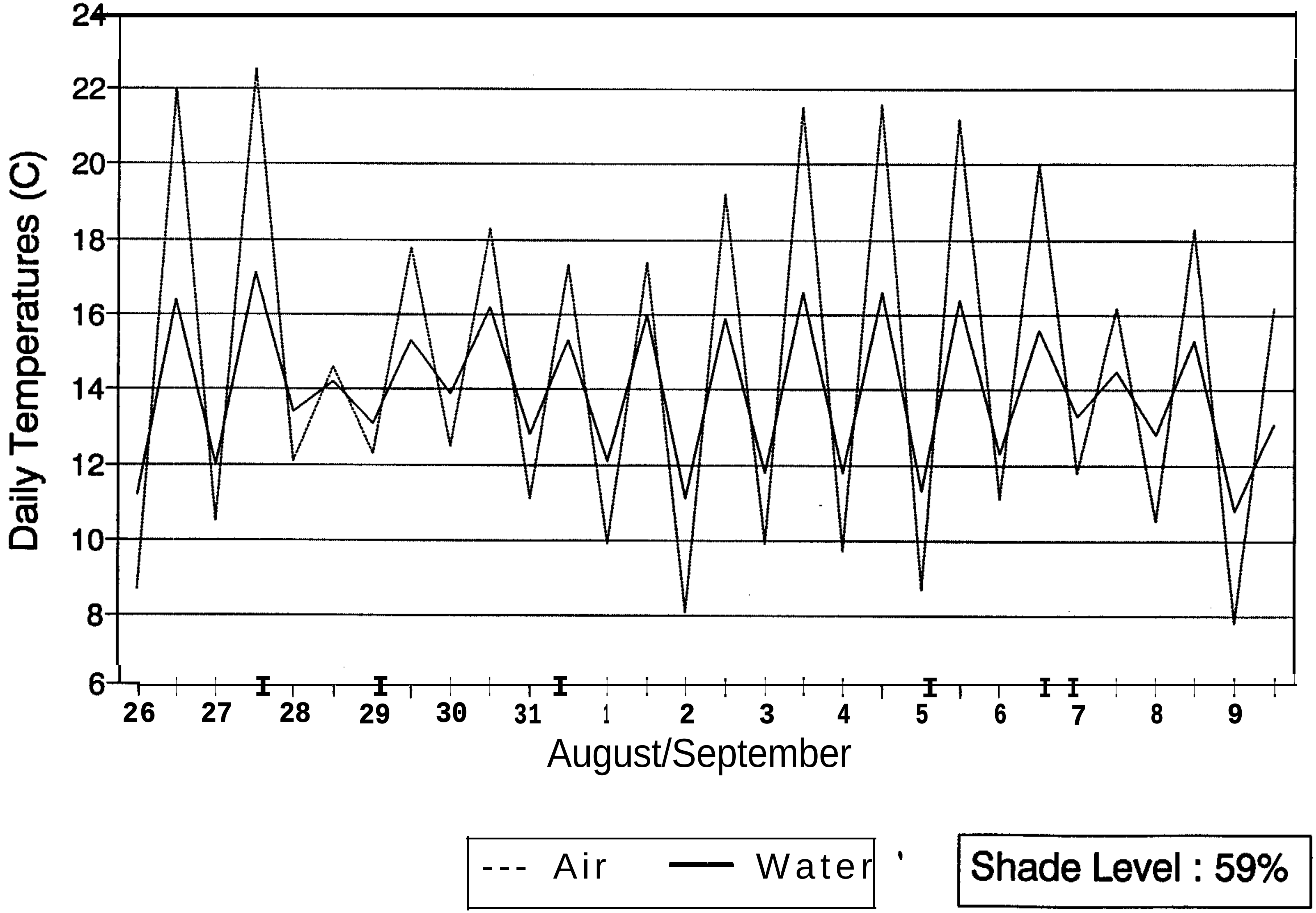




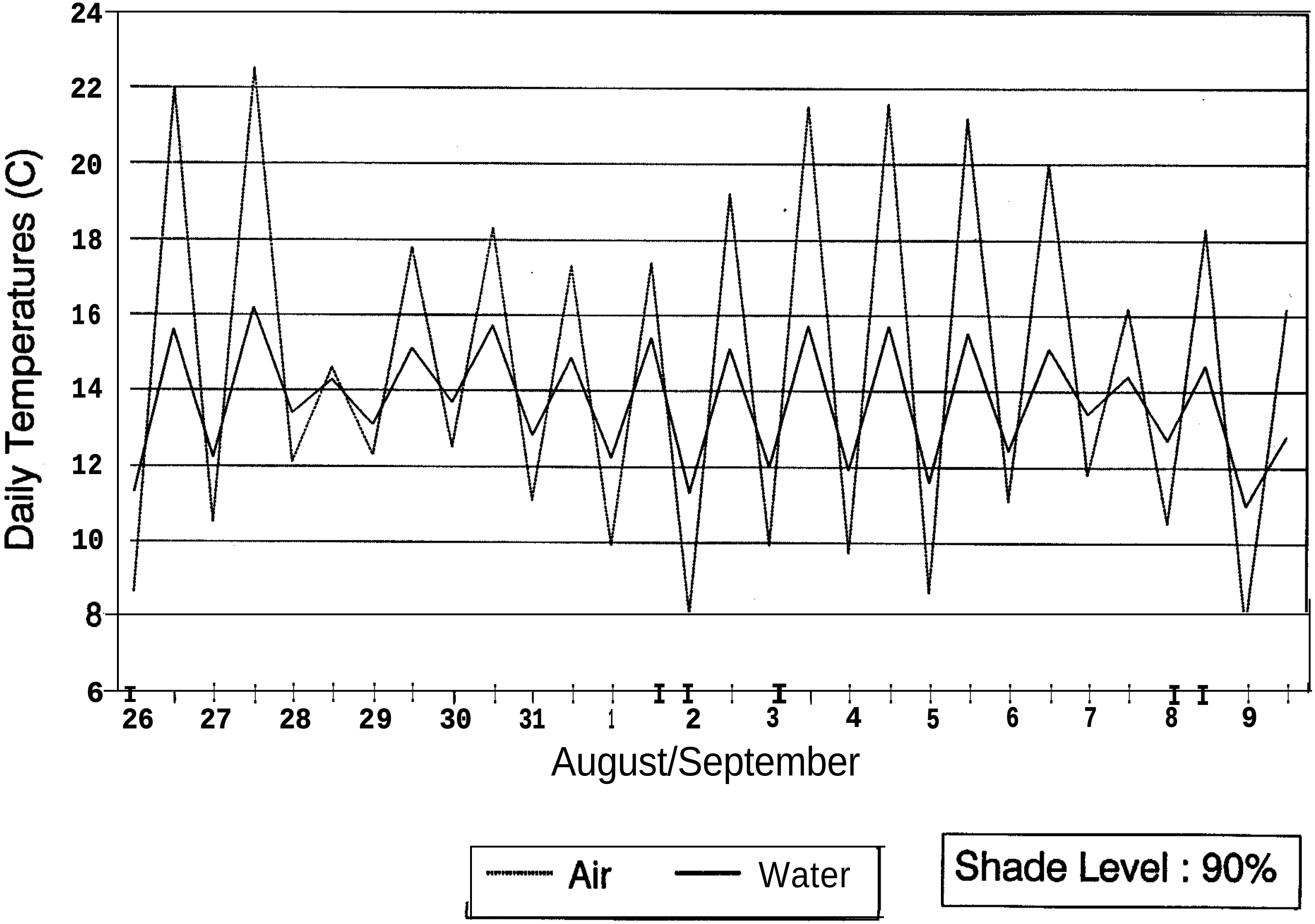
Jimmy Come Lately Creek Site C
Type 4 Harvested
Daily Temperatures (C)
0
5
10
15
20
25
30
35
40
26
27
28
29
30
31
1
2
3
4
5
6
7
8
9
August/September
--- Air
Water
Shade Level : 3%

Jimmy Come Lately Creek Site D

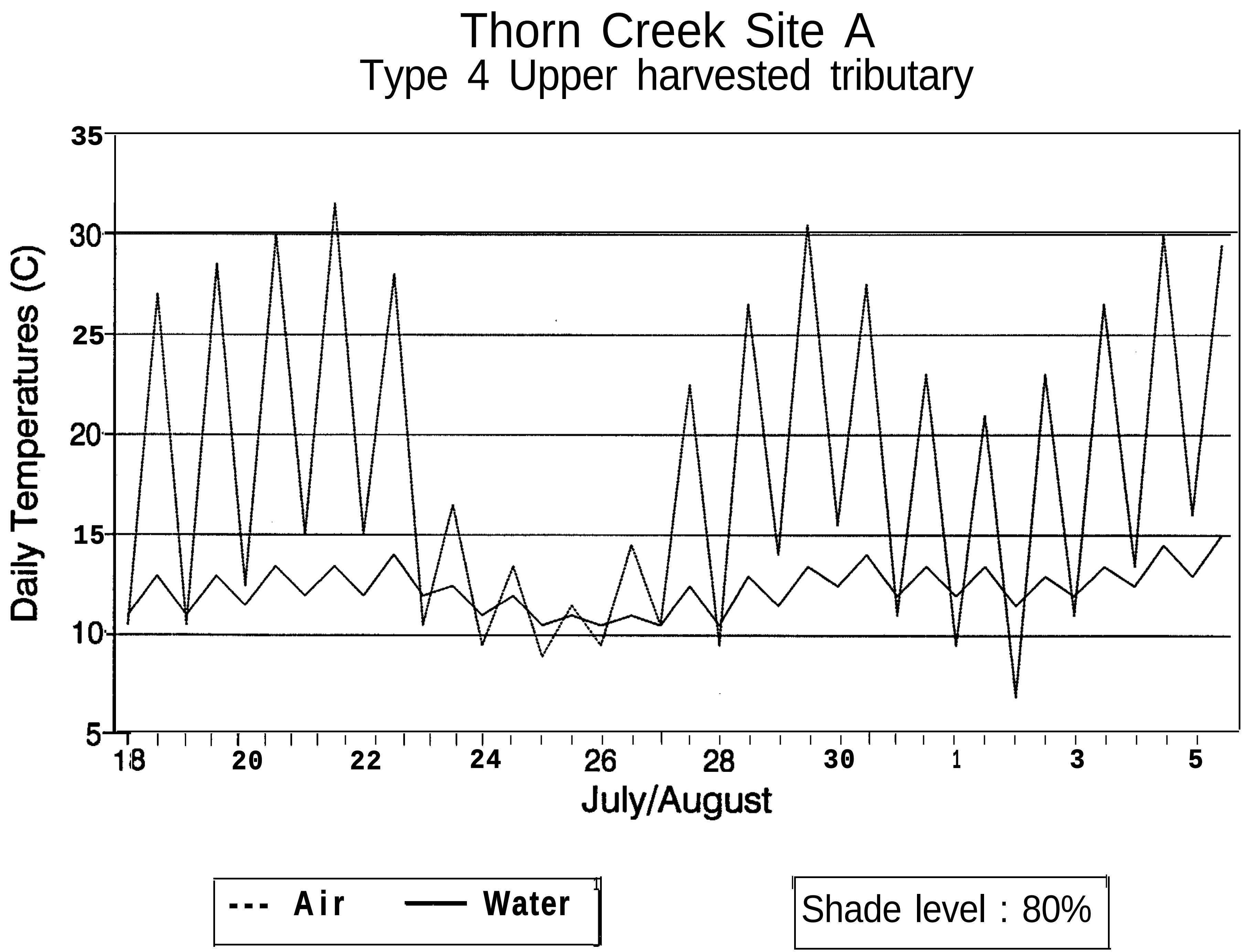
Type 3 Selective harvest riparian



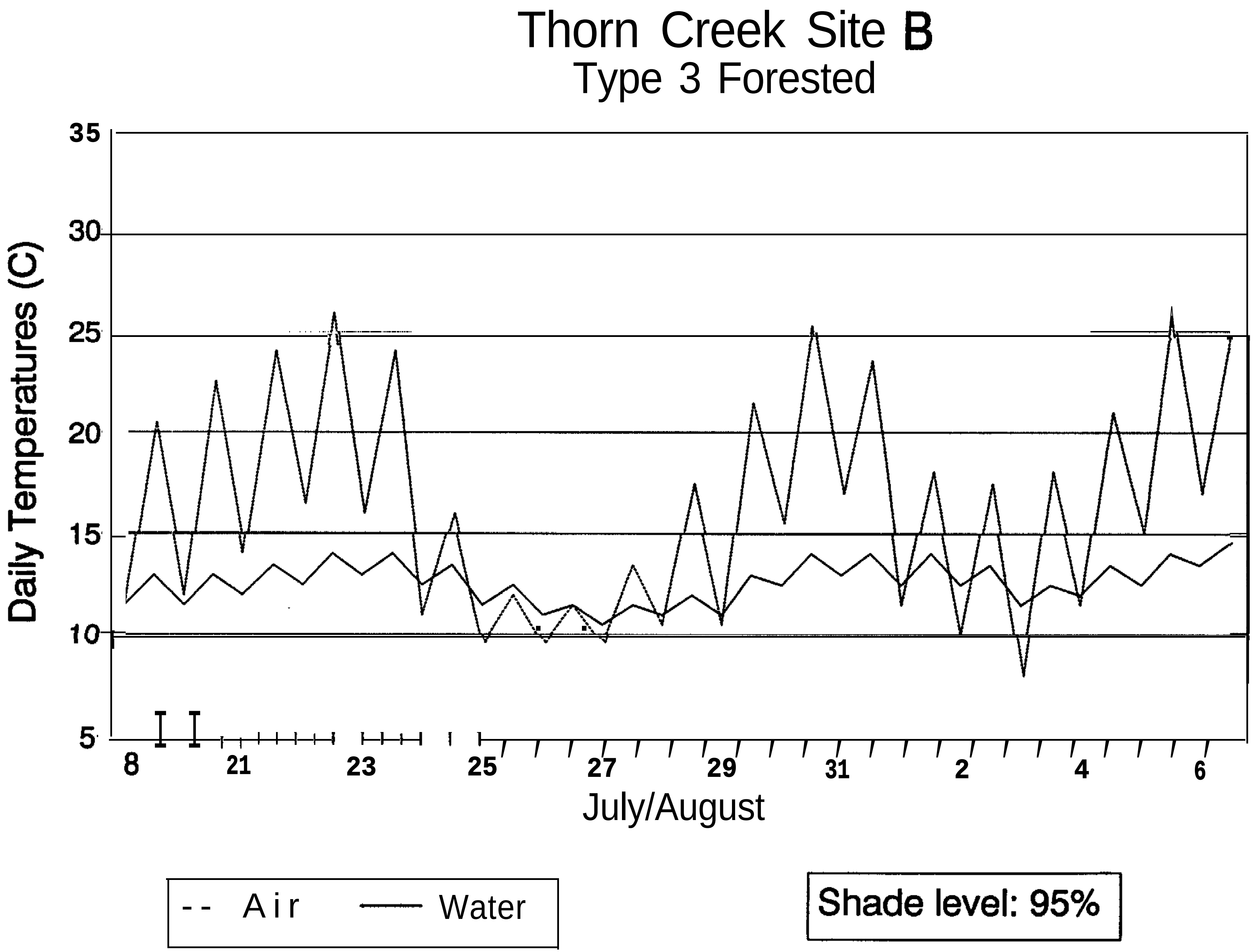
Jimmy Come Lately Creek Site E
Type 3 Selective harvest riparian



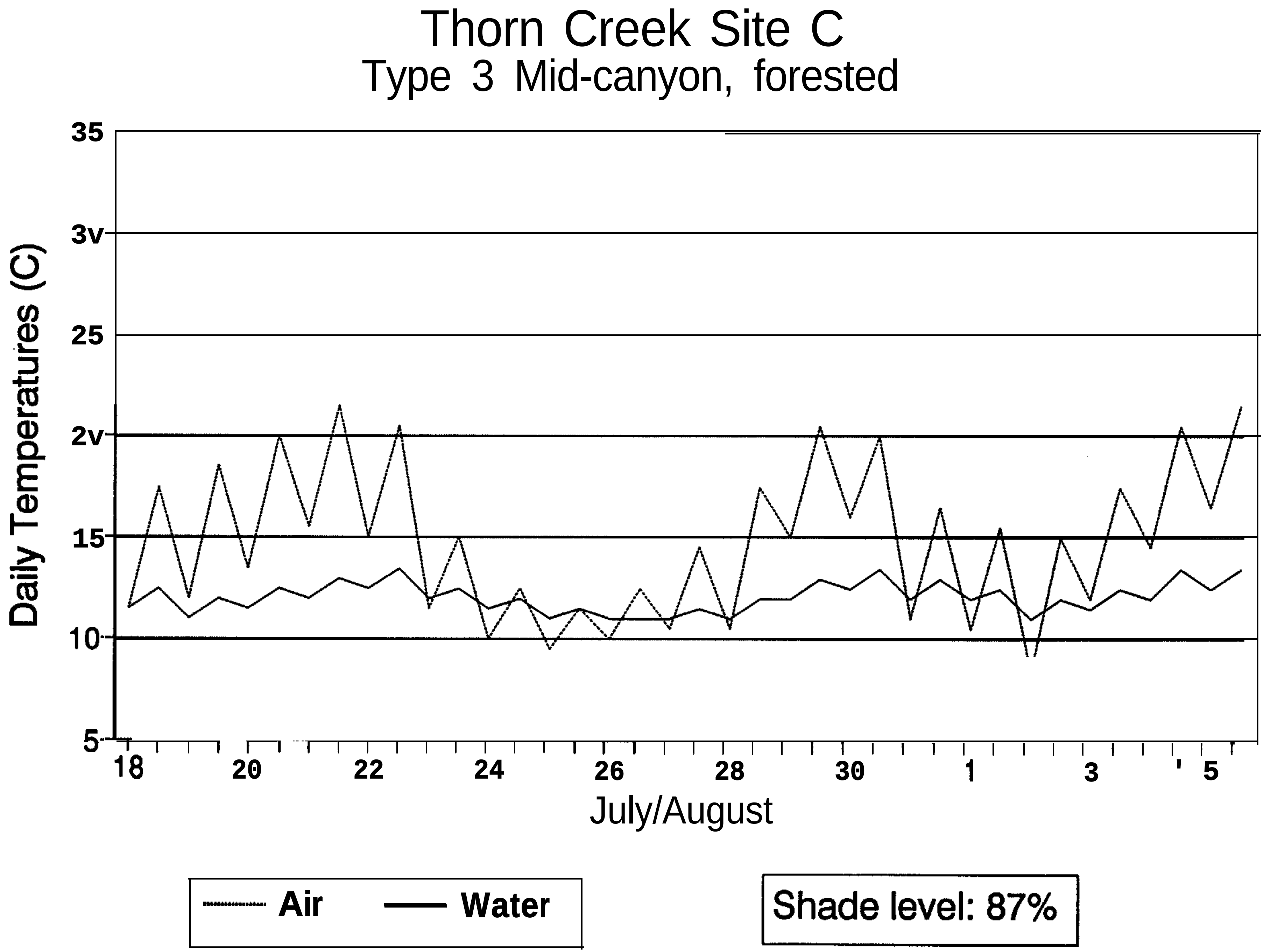
Shade Level : 90%



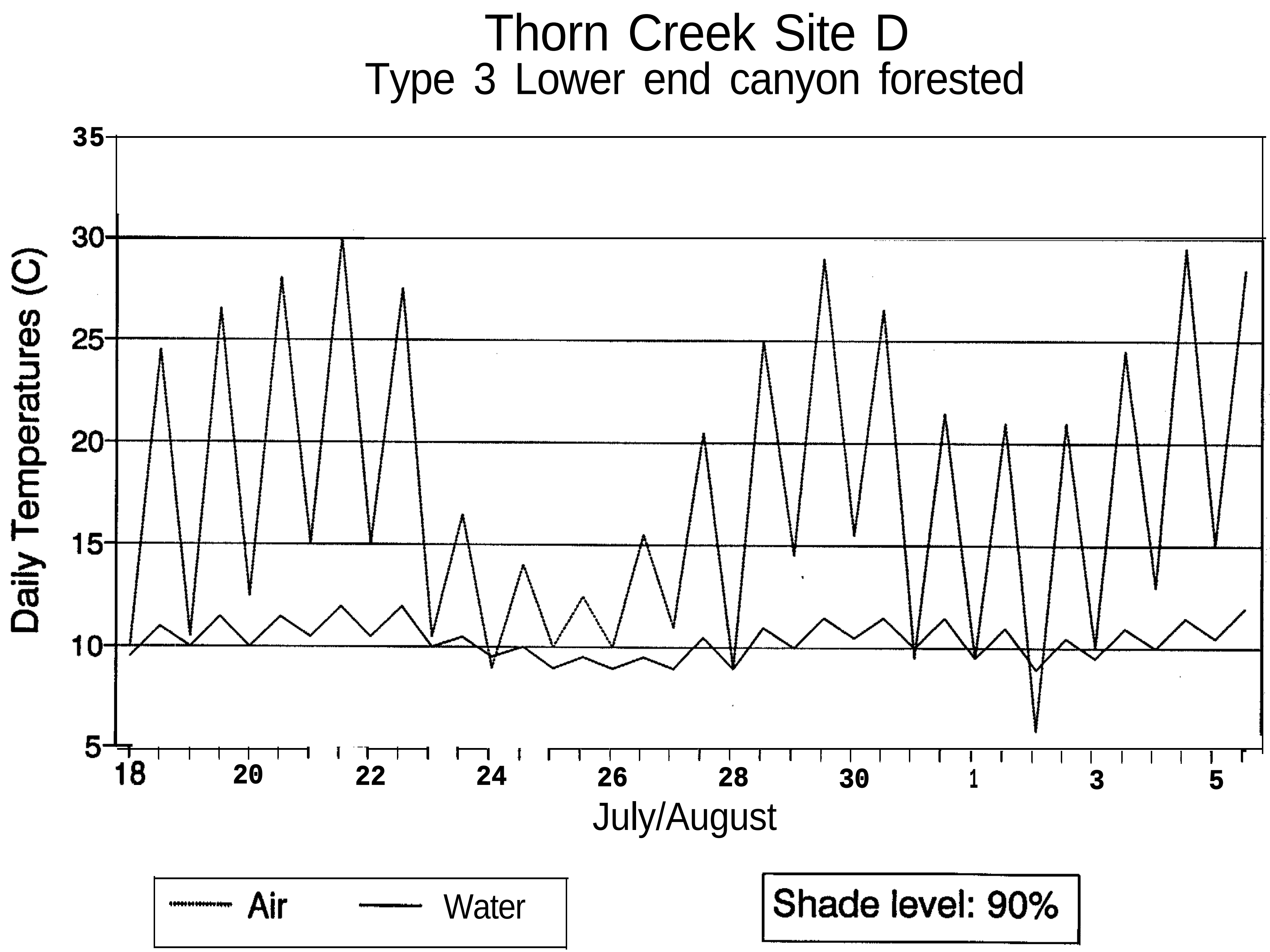
Thorn Creek Site A
Type 4 Upper harvested tributary
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
--- Air
Water
Shade level : 80%

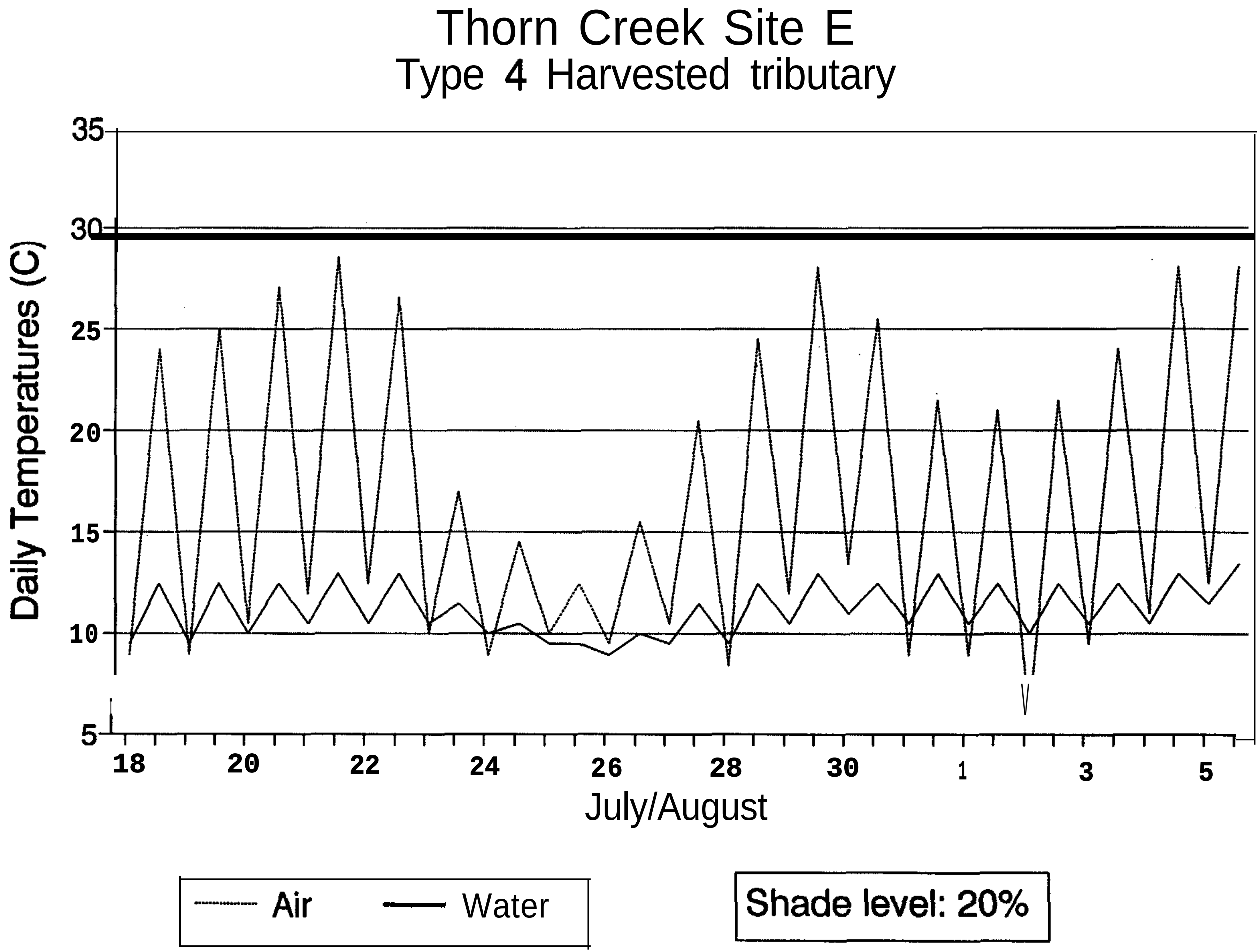


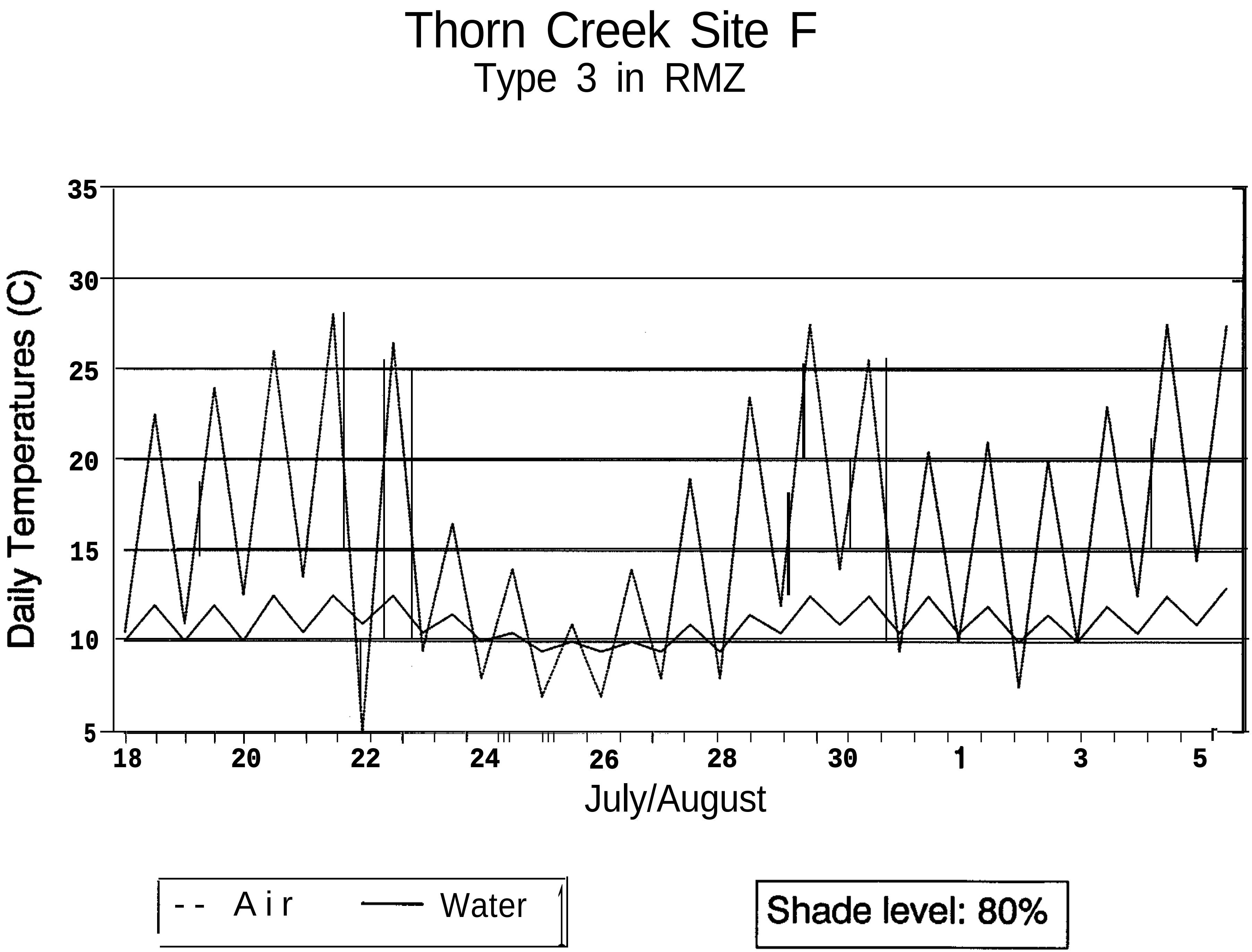
Thorn Creek Site B
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
8
21
23
25
27
29
31
2
4
6
July/August
-- Air
Water
Shade level: 95%



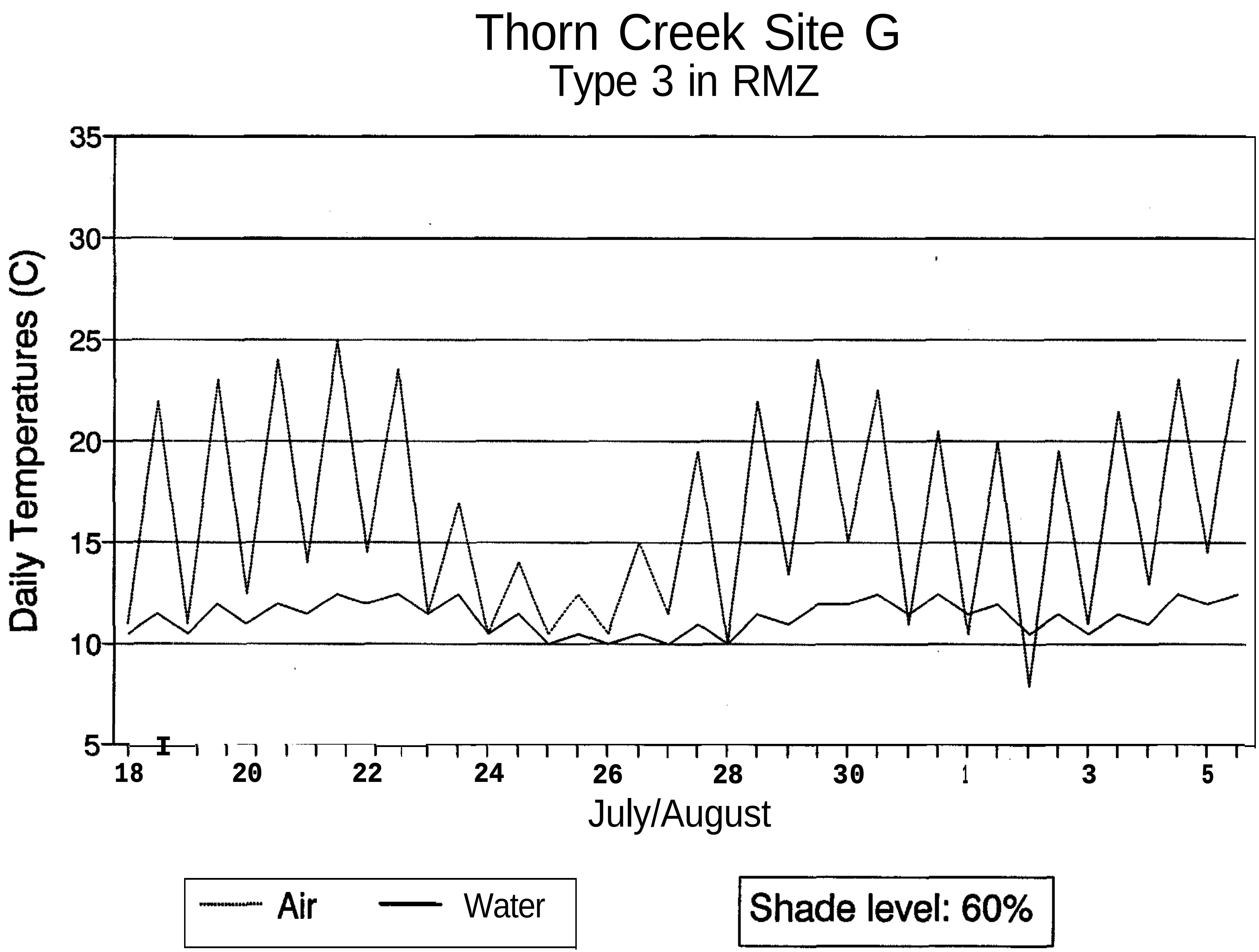
Thorn Creek Site C
Type 3 Mid-canyon, forested
Daily Temperatures (C)
35
3v
25
2v
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 87%


Thorn Creek Site D
Type 3 Lower end canyon forested
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 90%


Thorn Creek Site E
Type 4 Harvested tributary
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 20%

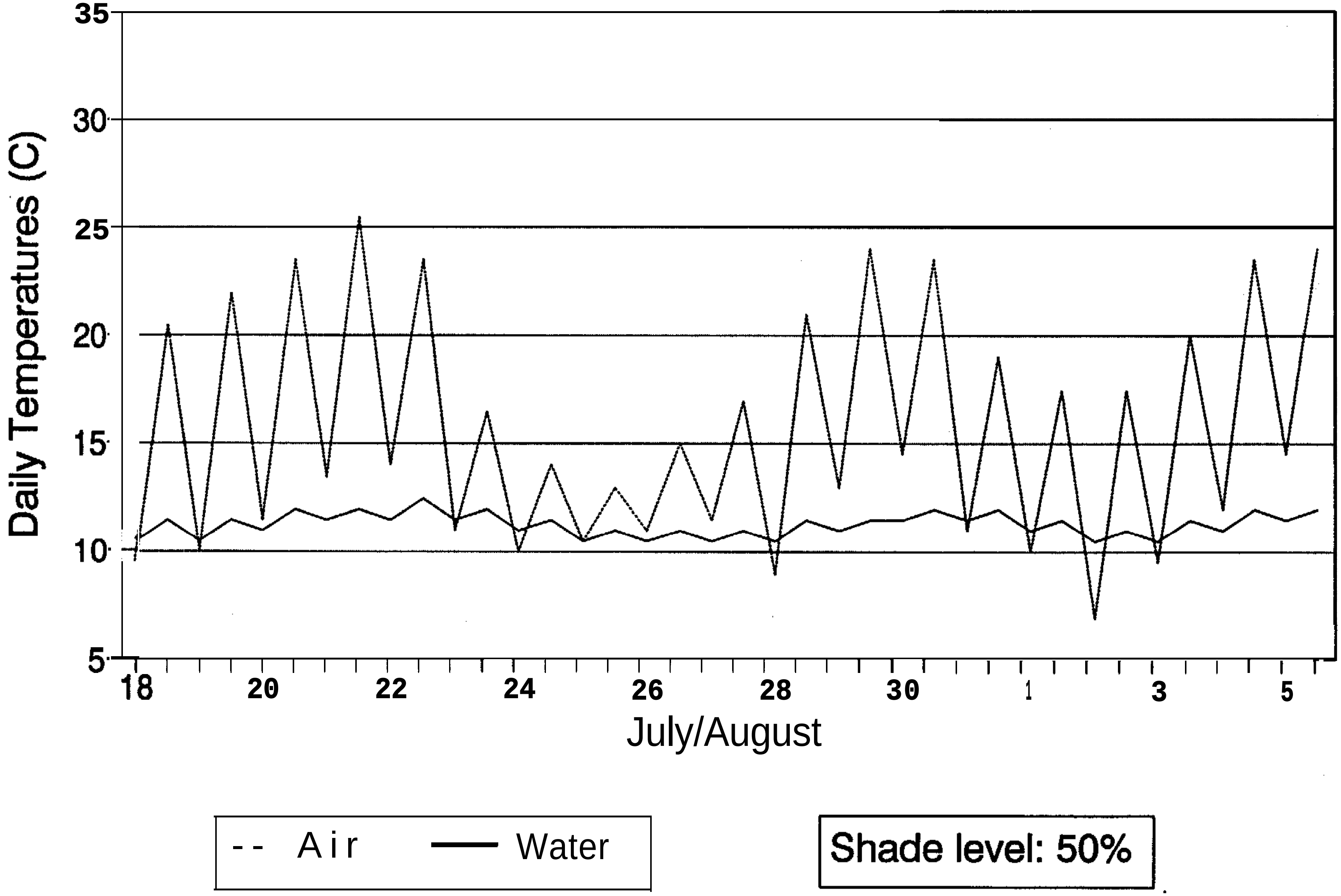


Thorn Creek Site F
Type 3 in RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
-- Air
Water
Shade level: 80%

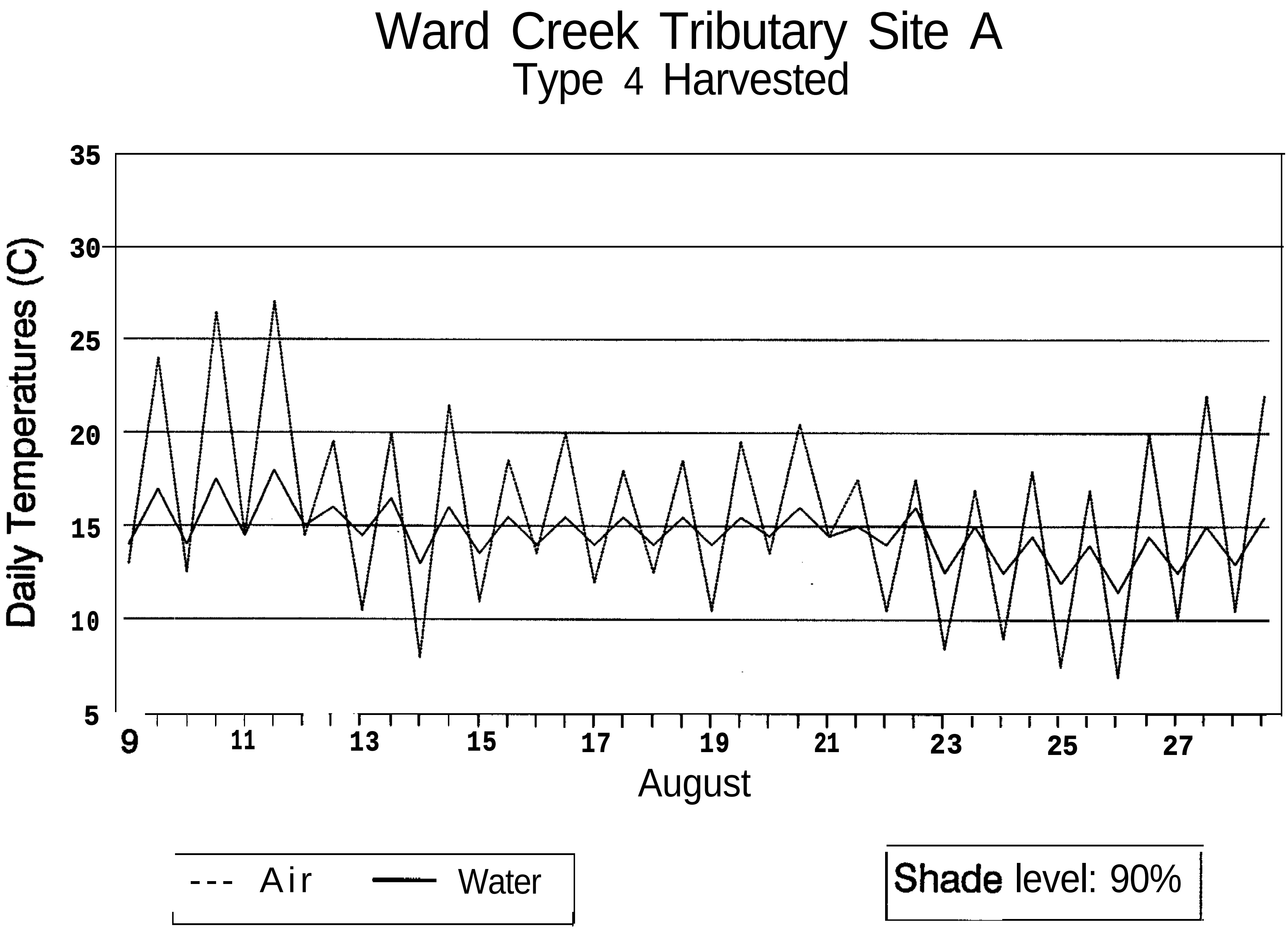


Thorn Creek Site G
Type 3 in RMZ
Daily Temperatures (C)
35
30
25
20
15
10
5
18
20
22
24
26
28
30
1
3
5
July/August
Air
Water
Shade level: 60%

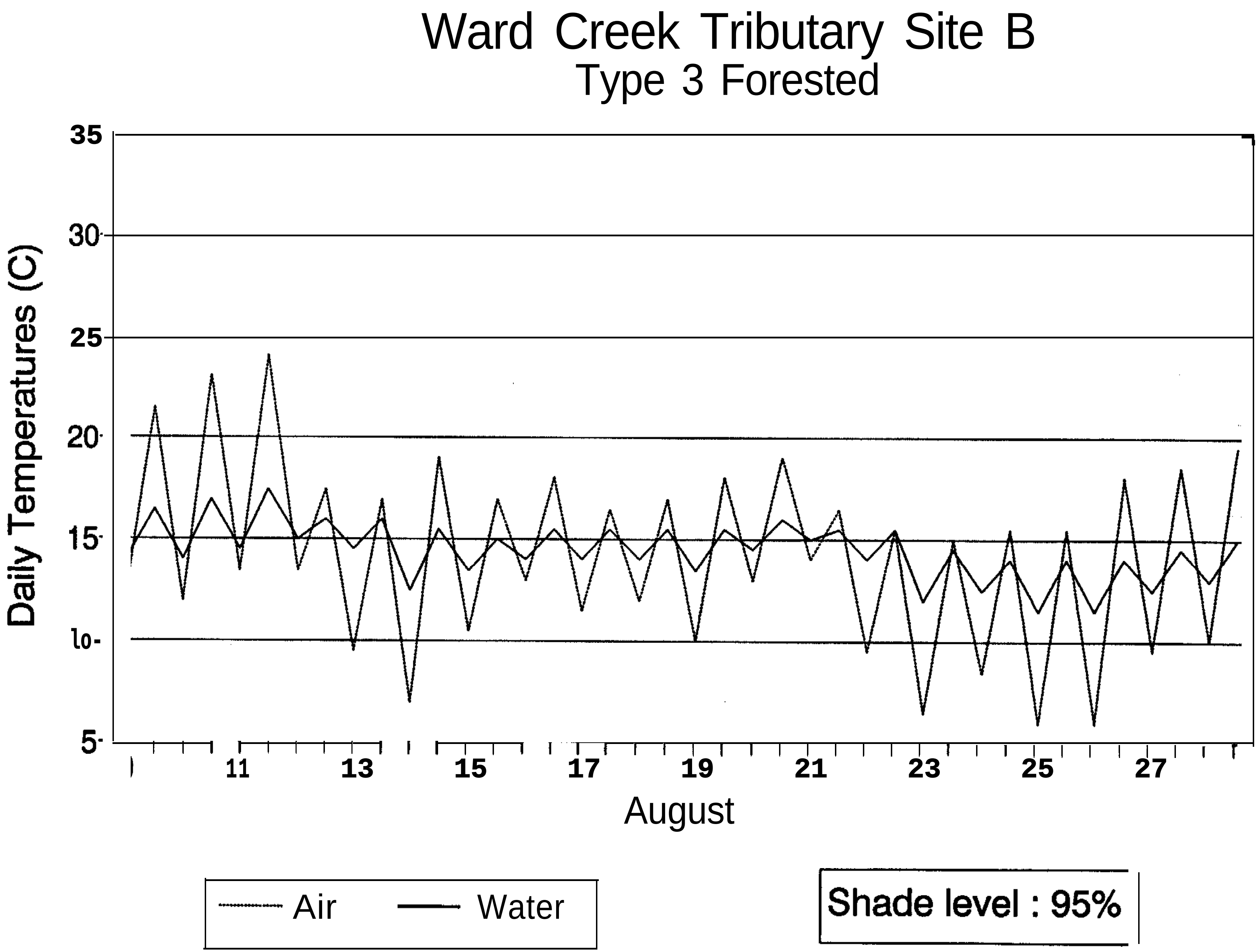
Thorn Creek Site H
Type 3 in RMZ



Shade level: 50%

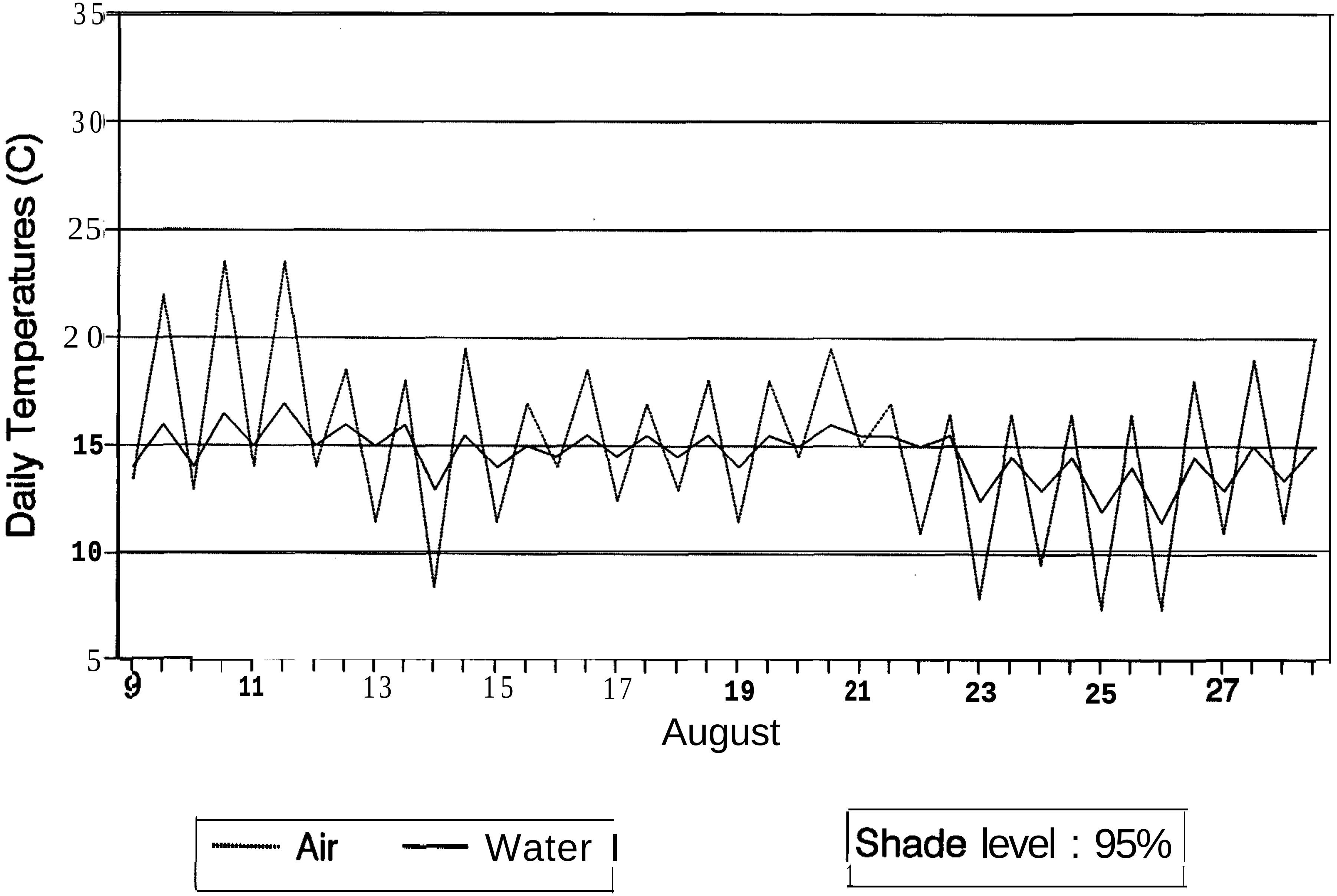


Ward Creek Tributary Site A
Type 4 Harvested
Daily Temperatures (C)
35
30
25
20
15
10
5
9
11
13
15
17
19
21
23
25
27
August
--- Air
Water
Shade level: 90%

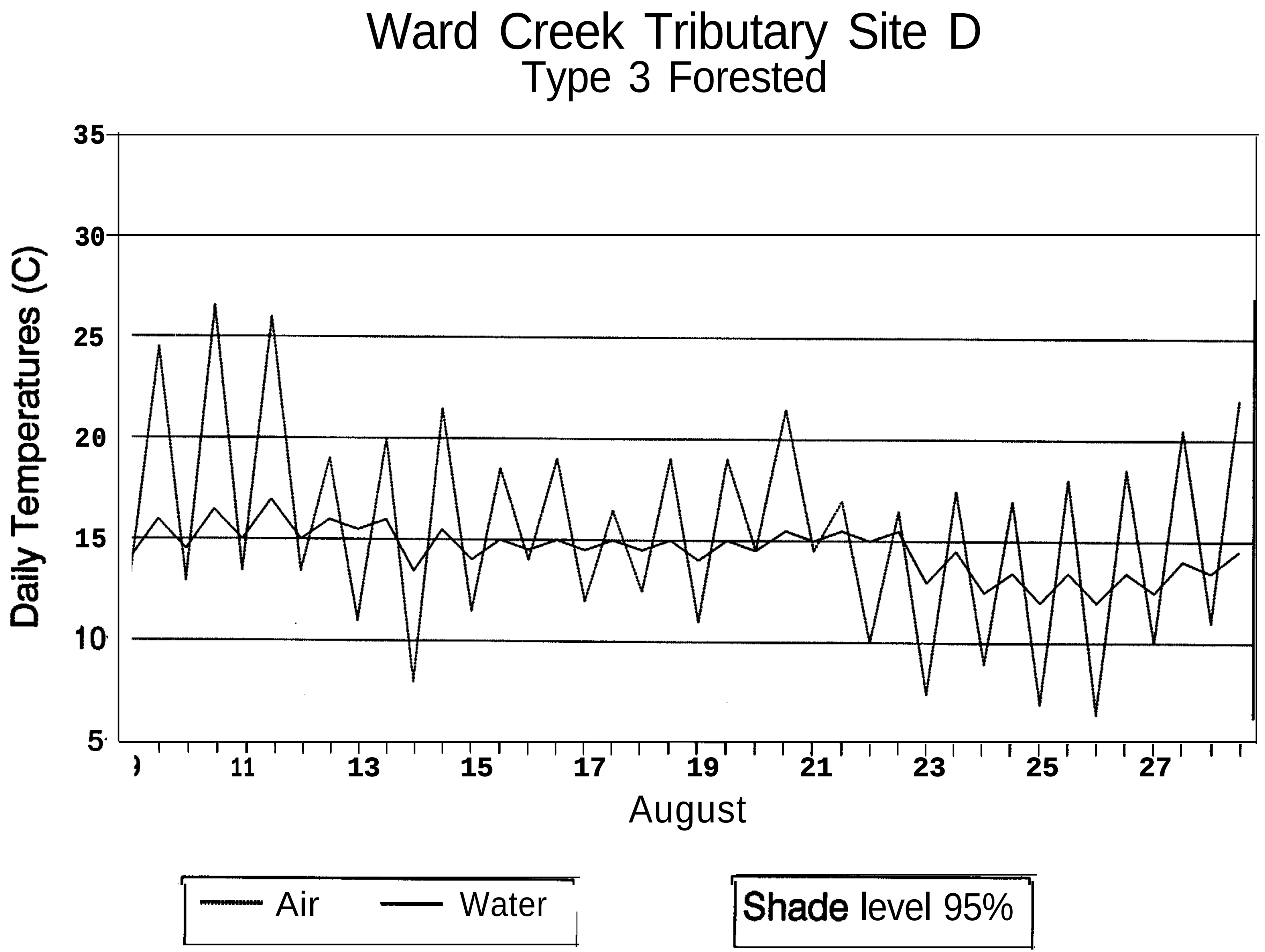


Ward Creek Tributary Site B
Type 3 Forested
Daily Temperatures (C)
35
30
25
20
15
10
5
11
13
15
17
19
21
23
25
27
August
Air
Water
Shade level : 95%

Ward Creek Tributary Site C
Type 3 Forested



Shade level : 95%



Ward Creek Tributary Site D
Type 3 Forested
35
30
25
20
15
10
5
Daily Temperatures (C)
11
13
15
17
19
21
23
25
27
August
Air
Water
Shade level 95%